Quality of movement patterns in different groups of urban adolescents

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DOCTORAL THESIS

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Supervisor:
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Mentor:
Doc.dr.sc. Maroje Sorić

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SUPERVISOR INFORMATION

Maroje Sorić was born in 1979 in Zagreb (Croatia). He currently serves as an Assistant Professor and the Head of the Physical Activity Measurement and Surveillance Laboratory at the University of Zagreb. At the same time, he acts as a Research Associate at the University of Ljubljana where he participates in monitoring and evaluating fitness of school-children (SLOfit). He qualified as a medical doctor at the Zagreb School of Medicine (Croatia) in 2003 and earned his PhD in Biomedicine at the same institution in 2010. His main scientific interests relate to the objective measurement of physical activity and sleep and the relationships of physical activity and inactivity with health and disease. Since the beginning of his career, he has been focused on the interrelationships of physical activity, sedentary behaviours and sleep with various health outcomes. His global perspective is reflected in his work in the NCD Risk Factor Collaboration (NCD-RisC), a network of health scientists that provides rigorous and timely data on major risk factors for non-communicable diseases for all of the world's countries. From 2016 when he became one of the central members of the NCD-RisC, he has been monitoring global prevalence and trends in obesity and high blood pressure in both adults and children. Among several papers in which he was centrally involved, three articles stand out: two were published in the Lancet and one in Nature. Up to date he published 52 scientific papers, 39 of which were published in journals indexed in the Web of Science. According to the Google scholar, his work received 8730 citations up to date, h-index=18 (accessed 01.02.2021). During his career dr. Sorić was involved in numerous scientific projects relating to the field of physical activity and health. At present, he is leading the work package on physical activity policies in a large European Commission funded project STOP, aimed at identifying policies to tackle childhood obesity across Europe. He was an invited speaker on several international scientific meetings and an active participant in more than 20 national and international scientific meetings. He served as a reviewer in numerous WOS-indexed international scientific journals (Journal of Science and Medicine, Annals of Nutrition and Metabolism, International Journal of Sport Nutrition & Exercise, BMC Public Health, BMC Pediatrics, Perceptual and Motor Skills, Annals of Human Biology, etc.). In 2007-2010 he formed a part of an expert panel formed by the Government of the Republic of Croatia that conceived the 'National action plan for the prevention of obesity 2010-2012'.

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List of abbreviations:

95% CI – 95 percent confident interval

AI – artificial intelligence

AUC – area under the curve

BMI – body-mass index

CRO-PALS – Croatian Physical Activity in Adolescence Longitudinal Study

DFM – Dysfunctional movement

FM – Functional movement

FMS™ – Functional Movement Screen™

HC – hip circumference

IOTF – International Obesity Task Force criteria

kNN – k-nearest neighbours

ML – machine learning

MPA – Moderate physical activity

MVPA – moderate-to-vigorous physical activity

OR – odd ratio

PA – physical activity

S4S – sum of 4 skinfolds

SES – socioeconomic status

SFT – skinfold thickness

SHAPES – School Health Action, Planning and Evaluation System

total FMS score – total Functional Movement Screen score

VPA – vigorous physical activity

WC – waist circumference

WHO – World Health Organization

WHtR - waist-to-height ratio

Table of contents

Musculoskeletal injuries

ABSTRACT

The main purpose of this doctoral thesis is to determine in which way are level of physical activity (PA), adiposity, and injury related to the quality of movement patterns among adolescent population. Within this doctoral thesis, there are three distinct studies with related research questions and aims (Study 1, Study 2, and Study 3). Study 1 examined relationship between functional movement and PA in an urban adolescent population, while study 2 strive to identify association between adiposity and quality of movement patterns among the adolescent population. Finally, in Study 3, machine learning (ML) was used to predict injuries among adolescents by functional movement testing. Participants in all three studies were part of the Physical Activity in Adolescence Longitudinal Study (CRO-PALS) cohort. In Study 1 we included 725 adolescents (aged between 16 and 17 years) from CRO-PALS cohort. Movement quality was evaluated via Functional Movement Screen^{TM} (FMS^{TM}) while PA was assessed with the School Health Action, Planning and Evaluation System (SHAPES) questionnaire. From SHAPES questionnaire, vigorous PA (VPA) and moderate-to-vigorous PA (MVPA) was calculated. Confounders included chronological age, body fat and socioeconomic status (SES). Results of Study 1 indicated that after adjusting for age, body fat and SES, both VPA and MVPA showed minor but significant effects on total FMS score among girls (β=0.011, p=0.001, β=0.005, p=0.006, respectively), but not in boys (β=0.004, p=0.158; β=0.000, p=0.780). Regarding PA type, volleyball and dance improved total FMS score (β=1.003, p=0.071; β=0.972, p=0.043, respectively), while football was associated with lower FMS score (β=-0.569, p=0.118). Conclusively, results of Study 1 showed that PA level is positively associated with the functional movement in adolescent girls, but not in boys, where the type of PA moderates these associations. Because girls are more engaged in aesthetic sports activities that improve functional movement, and unlike boys are in the final stages of maturation, this could affect sexual dimorphism in the quality of movement among the adolescent population. In Study 2 participants were 652 urban adolescents (aged between 16 and 17 years). Body mass index (BMI), a sum of four skinfolds (S4S), waist and hip circumference were measured, and movement quality (i.e. functional movement – FM) was assessed via FMS^{TM}. Furthermore, total FMS^{TM} screen was indicator of FM with the

composite score ranged from 7 to 21, with higher score indicating better FM. Multilevel analysis was employed to determine the relationship between different predictors and total FMS score. Results of the Study 2 demonstrate that, in boys, after controlling for age, MVPA, and SES, total FMS score was inversely associated with BMI (β=-0.18, $p<0.0001$), S4S (β=-0.04, $p<0.0001$), waist circumference (β=-0.08, $p<0.0001$), and hip circumference (β=-0.09, $p<0.0001$). However, among girls, in adjusted models, total FMS score was inversely associated only with S4S (β=-0.03, $p<0.0001$), while BMI (β=-0.05, p=0.23), waist circumference (β=-0.04, p=0.06), and hip circumference (β=-0.01, p=0.70) failed to reach statistical significance. Findings of Study 2 point out that the association between adiposity and FM in adolescence is sex-specific, suggesting that boys with overweight and obesity could be more prone to develop dysfunctional movement patterns. Therefore, exercise interventions directed toward correcting dysfunctional movement patterns should be sex-specific, targeting more boys with overweight and obesity rather than adolescent girls with excess weight. Analyses for the Study 3 were based on nonathletic (n=364) and athletic (n=192) subgroups of the cohort (16–17 years). Sex, age, BMI, body fatness, MVPA, training hours per week, FMS, and SES were assessed at baseline. A year later, data on injury occurrence were collected. The optimal cut-point of the total FMS score for predicting injury was calculated using receiver operating characteristic curve. These predictors were included in ML analyses with calculated metrics: area under the curve (AUC), sensitivity, specificity, and odds ratio (95% confidence interval [CI]). Results of the receiver operating characteristic curve analyses with associated criterium of total FMS score >12 showed AUC of 0.54 (95% CI: 0.48–0.59) and 0.56 (95% CI: 0.47–0.63), for the nonathletic and athletic youth, respectively. However, in the nonathletic subgroup, ML showed that the Naïve Bayes exhibited highest AUC (0.58), whereas in the athletic group, logistic regression was demonstrated as the model with the best predictive accuracy (AUC: 0.62). In both subgroups, with given predictors: sex, age, BMI, body fat percentage, MVPA, training hours per week, SES, and total FMS score, ML can give a more accurate prediction then FMS alone. Results of the Study 3 indicate that nonathletic boys who have lower-body fat could be more prone to suffer from injury incidence, whereas among athletic subjects, boys who spend more time training are at a higher risk of being injured. Conclusively, total FMS cut-off scores for each

subgroup did not successfully discriminate those who suffered from those who did not suffer from injury, and, therefore, this study does not support FMS as an injury prediction tool.

Key words: movement quality, Functional Movement Screen, sport participation, children, movement patterns, obesity, paediatric exercise, motor control, motor coordination, motor competence, movement competence, artificial intelligence, AI, adolescence, forecasting injury, musculoskeletal conditions

SAŽETAK

Cilj Glavni cilj ove doktorske disertacije bio je utvrditi odnos između razine tjelesne aktivnosti (TA), adipoznosti te pojavnosti ozljeda i kvalitete obrazaca pokreta u adolescentskoj populaciji. Ovom disertacijom bit će obuhvaćene tri studije sa tri različita cilja (Studija 1, Studija 2 i Studija 3). Studija 1 utvrdit će povezanost između funkcionalnog pokreta (FP) i razine TA. Studija 2 imala je za cilj utvrditi povezanost između adipoznosti i kvalitete obrazaca pokreta kod urbanih adolescenata. U Studiji 3 metodama strojnog učenja (SU) pokušat će se predviditi pojavnost ozlijede putem FMS^{TM} dijagnostičkog alata kod adolescenata u jednogodišnjem razdoblju. Sudionici koji su uključeni u navedene studije bili su dio opsežnije studije, Hrvatska longitudinalna studija tjelesne aktivnosti u adolescenciji (*Physical Activity in Adolescence Longitudinal Study* - CRO-PALS).

Metode Studija 1 U Studiji 1 bila su uključena 725 ispitanika u dobi od 16 do 17 godina. Procjena kvalitete pokreta napravljena je uz pomoć instrumenta FMS^{TM} (*Functional Movement screen^{TM}*) dok se razina TA procjenila SHAPES upitnikom (School Health Action, Planning and Evaluation System). Iz podataka koji su dobiveni SHAPES upitnikom, izračunata je umjerena TA (UTA) te umjereno do žustra TA (UŽTA). Kao kovariajble, u svim analizama bile su uključene sljedeće varijable: kronološka dob, postotak tjelesne masti i socioekonomski status (SES).

Rezultati Studija 1 Nakon što su analize bile podešene za kronološku dob, postotak tjelesne masti i SES, rezultati Studije 1 ukazuju da su UŽTA i UTA bile su značajno i pozitivno povezne sa sveukupim FMS rezultatom kod djevojčica (β=0.011, p=0.001, β=0.005, p=0.006), ali ne i kod dječaka (β=0.004, p=0.158; β=0.000, p=0.780). U dodatnim analizama, sudjelovanje u odbojci (β=1.003, p=0.071) i plesu (β=0.972, p=0.043) bilo je pozitivno povezano sa sveukupnim FMS rezultatom, dok je nogomet bio u negativnoj relaciji sa sveukupnim FMS rezultatom (β=-0.569, p=0.118).

Zaključak Studija 1 Zaključno, razina TA je pozitivno povezana sa kvalitetom obrazaca pokreta kod djevojčica, dok kod dječaka te relacije nisu bile naznačene. Potencijalno objašnjnje uključuje to da se djevojčice nalaze u kasnijoj fazi sazrijavanja te su više uključene

u estetske sportove koji unapređuju kvalitetu obrazaca kretanja. Također, utvrđeno je da vrsta TA moderira povezanost između kvalitete obrazaca pokreta i razine TA kod oba spola.

Metode Studija 2 U Studiji 2 sudjelovalo je 652 ispitanika (16-17 god.) te su izmjerene sljedeće varijable: suma četri kožna nabora (S4S), opseg struka, opseg kukova te je izračunat indeks tjelesne mase (ITM). Kvaliteta pokreta (tj. funkcionalni pokret – FM) evaluirana je putem FMS^{TM} dijagnostičkog instrumenta. Veći broj bodova na FMS^{TM} skali ukazivao je na bolju kvalitetu pokreta dok je krajnji rezulat bio sveukupni FMS rezultat s rasponom bodova od 7 do 21. Za obradu podataka koristile su se metode višerazinskog modeliranja.

Rezultati Studija 2 Nakon što su analize bile podešene za kronološku dob, UŽTA i SES, kod dječaka je sveukupni FMS rezulat bio negativno povezan sa ITM-om ($\beta=-0.18$, $p<0.0001$), S4S ($\beta=-0.04$, $p<0.0001$), opsegom struka ($\beta=-0.08$, $p<0.0001$) te opsegom kukova ($\beta=-0.09$, $p<0.0001$). Kod djevojčica, jedino je S4S bio u negativnoj relaciji sa sveukupnim FMS rezultatom ($\beta=-0.03$, $p<0.0001$), dok ostali prediktori nisu pokazali statističku značajnost (ITM: $\beta=-0.05$, $p=0.23$; opseg struka: $\beta=-0.04$, $p=0.06$; opseg kukova: $\beta=-0.01$, $p=0.70$).

Zaključak Studija 2 Rezultati Studije 2 ukazuju da je povezanost između adipoznosti i kvalitete obrazaca pokreta specifična po spolu, gdje su dječaci sa prekomjenom tjelesnom težinom skloniji razvoju disfunkcionalnih obrazaca pokreta. Stoga, intervencije i programi vježbanja bi trebali biti više usmjereni na korekciji disfunkcionalnih obrazaca pokreta kod dječaka sa prekomjernom tjelesnom težinom nego kod djevojčica veće tjelesne mase.

Metode Studija 3 Analize za Studiju 3 temelje se na dvije podskupine adolescenata, sportaše (n=364) i nesportaše (n=192) (16-17 god.). Prediktori uključeni u analizama SU bili su: spol, dob, ITM, postotak tjelesne masti, UŽTA, broj trenažnih sati tjedno, kvaliteta obrazaca pokreta (izmjerena FMS-om) i SES. Godinu dana kasnije, podaci o ozljedama dobiveni su kompjuteriziranim upitnikom konstruiranim za potrebe ovog istraživanja. Za utvrđivanje granične vrijednosti sveukupnog FMS rezultata koji će uspješno predvidjeti rizik od ozljeđivanja, koristila se analiza krivulje osjetljivosti (*engl. Receiver operating characteristics - ROC*) gdje se izračunala površina ispod krivulje (*engl. area under the curve*

- AUC). Također, izračunata je osjetljivost, specifičnost, te omjer izgleda uz pripadajuće intervale pouzadanosti (95% CI) za svaki od prediktivnih modela dobivenih putem SU.

Rezultati Studija 3 Rezultati studije 3 pokazuju da je ROC analiza sa pridruženim kriterijom sveukupnog FMS rezultata >12 pokazala skromnu točnost u populaciji nesportša (AUC: 0.54; 95% CI: 0.48–0.59), dok je u nesportskoj populaciji točnost bila veća (AUC: 0.56; 95% CI: 0.47–0.63). Među metodama SU, metoda Naïve Bayes dala je najtočniji prediktivni model u podskupini nesportaša (AUC: 0.58). S druge strane, u podskupini sportaša, logistička regresija pokazala se kao metoda sa najuspješnijom prediktivnim modelom (AUC: 0.62). U obje podskupine, sa prediktorima: spol, dob, ITM, postotak tjelesne masti, UŽTA, broj trenažnih sati tjedno, kvalitetom obrasca pokreta i SES, SU daje točniju predikciju u usporedbi sa predikcijama dobevnim FMS^{TM} dijagnostičkim instrumentom.

Zaključak Studija 3 Rezultati Studije 3 ukazuju da su dječaci nesportaši, koji imaju manji postotak masti, skloniji većem riziku za ozljeđivanje. S druge strane, dječaci koji se bave sportom i koji provode više vremena trenirajući imaju najveći rizik za pojavnost ozljede. Zaključno, sveukupni FMS rezultat ne može uspješno predvidjeti pojavnost ozljeđivanja u populaciji sportaša i nesportaša. Stoga ova studija ne preporuča korištenje FMS dijagnostičkog instrumenta u cilju predikcije ozljeda.

Ključne riječi: kvaliteta pokreta, Functional Movement Screen, sudjelovanje u sportu, djeca, obrasci pokreta, pretilost, pediajtrijska populacija i vježbanje, motorička kontrola, koordinacija, motoričko znanje, umjetna inteligencija, UI, adolescencija, predviđanje ozljeda, mišićnokoštani sindromi

THESIS OUTLINE

This thesis contains four chapters. In chapter one general introduction to the scientific problem as well as the research aims and questions are covered. Chapter two describes basic concepts and definitions (i.e. movement quality, PA, adiposity, and musculoskeletal injury). In chapter three, published articles included in this thesis are presented. The first study investigated the relationship between functional movement and PA in an urban adolescent population (Study 1). The second study tried to determine is adiposity associated with the quality of movement patterns in the mid-adolescent period (Study 2). The third study aims to predict injuries via functional movement quality in a one-year period by using ML in a representative sample of urban athletic and non-athletic adolescents (Study 3). Chapter four provides a general conclusion of all three presented studies. Also, in chapter four, strengths and limitations as well as perspectives for future research are described. In the end, appendices of Study 1 and Study 2 are attached.

INTRODUCTION

Context

Insufficient physical activity (PA) is related to many noncommunicable diseases, shortened life expectancy (Department of Health & Human Services, 2018), leading to a large economic burden and global health problem (Ding et al., 2016). Recent reports have shown that inactive children are exposed to increased metabolic and cardiovascular risk (Janssen & LeBlanc, 2010). Several studies point to the positive effects of regular PA on physical, cognitive, and mental health in children (Janssen & LeBlanc, 2010). In addition to the negative consequences of physical inactivity, low levels of PA have been related to suboptimal proprioception (Ribeiro & Oliveira, 2011) and possible decreases in neuromuscular innervation. More importantly, evidence shows that extremely low levels of PA can lead to loss of muscle volume, physiological cross-sectional area, loss of fascicle length, changes of pennation angle and muscle strength as well as deficits in motor control (Campbell et al., 2013) which can potentially lead to suboptimal movement quality (Duncan et al., 2013; Duncan & Stanley, 2012; Molina-Garcia et al., 2020).

Along with the consequences of insufficient PA, childhood obesity presents one of the largest public health problems with serious long-term health consequences. Children with obesity have a higher risk of developing diabetes type 2, cardiovascular diseases, cancer, and musculoskeletal disorders later in life (Krul et al., 2009; Merder-Coşkun et al., 2017; Weihrauch-Blüher et al., 2019). Amongst the above-mentioned risks of paediatric obesity, musculoskeletal disorders with associated biomechanical and health impact have been least studied systematically. According to the most recent umbrella review which investigated the association between adiposity and physical function in children with obesity, few published systematic reviews drew attention to the phenomena of the biomechanics of childhood obesity (Tsiros et al., 2020). Indeed, only one review pointed to the negative influence of excess weight on movement biomechanics among children with possible long-term consequences on musculoskeletal health (Molina-Garcia et al., 2019). In addition to this, it is well known that pathobiomechanical behaviour is a key factor for the development of postural and musculoskeletal pathologies in children and adults (Aderem &

Louw, 2015; Boling et al., 2009; Kozak et al., 2015; Mahmoud et al., 2019). However, it remains unknown what role adolescent obesity plays in the development of different pathobiomechanical movement behaviour.

According to the recent evidence, three inter-related clinical and biomechanical components are compromised in children with overweight: (1) body posture (Araújo et al., 2017; Brzeziński et al., 2019; Jankowicz-Szymańska et al., 2019; Lonner et al., 2015; Maciałczyk-Paprocka et al., 2017), (2) gait biomechanics (Catan et al., 2020; Molina-Garcia, Migueles, et al., 2019), and (3) movement competence (Duncan et al., 2013; Duncan & Stanley, 2012; Pill & Harvey, 2019; Tsiros et al., 2020). Along with the postural abnormalities and altered biomechanics of walking, children with overweight have compromised movement competency (Pill & Harvey, 2019). Movement competency is defined as the global movement patterns (i.e., locomotion, object control skills, or stability tasks) essential for child motor development (Ahnert J, Schneider W, 2011; Stodden et al., 2008). An important aspect of the movement competency, and thus of motor development, is the qualitative component of the movement, often termed as the *movement quality*.

Functional movement (FM) represents a clinical measure of movement quality (Krause, 2014; Marques et al., 2017; Silva et al., 2019), most commonly assessed via Functional Movement Screen™ (FMS™) (Cook et al., 2006a, 2006b). FM implies an optimal range of motion, balance, and postural control of the specific movement (Cook, 2011; Cook et al., 2006a, 2006b). Contrary, dysfunctional movement (DFM) presents suboptimal movement quality and is related to a compensatory movement pattern along the kinetic chain with associated loss in the range of motion, balance, and deficit in postural control of the specific movement pattern (Cook, 2011; Cook et al., 2006a, 2006b). The importance of FM patterns has been discussed in previous studies (Cook et al., 2006a, 2006b; Krause, 2014; Marques et al., 2017; B. Silva et al., 2019) and they are considered as fundamental 'pillars' for the exhibition of complex movements (Cook et al., 2006a, 2006b). Several studies suggested that suboptimal movement quality, measured via FMS™, as one of the potential predictive factors of musculoskeletal injury in young and adult athletes. Indeed, DFM has been related to the higher incidence of musculoskeletal injury (Bonazza et al., 2017; Garrison et al., 2015; Kiesel et al., 2014; Shojaedin et al., 2014) and potential movement pathologies in children with overweight (Duncan et al., 2013; Duncan & Stanley, 2012; Molina-Garcia et al., 2020).

Incorporating FM patterns in exercise programs is critical for the optimal progress toward more complex movement skills (Cook, 2011; Cook et al., 2006a, 2006b). In addition to the aforementioned consequences of physical inactivity and obesity on FM, evidence shows that higher body weight changes motor performance, range of motion, balance (García-Pinillos et al., 2018) and leads to poor postural control in children (D'Hondt et al., 2008), which could potentially endanger the performance of both FM and complex movement skills. Evidence suggests that obesity has a high impact on joint structures responsible for joint stabilization and proprioception (Gushue et al., 2005). Furthermore, obesity leads to degenerative deformities such as osteoarthritis even among children (Widhalm et al., 2016). Taking everything into account, physical inactivity, overweight, and musculoskeletal injury in childhood could lead to the development of DFM and orthopaedic deformities in the future (Duncan et al., 2013; Duncan & Stanley, 2012; Molina-Garcia et al., 2020).

The development of DFM patterns along with the insufficient PA and higher body weight through the adolescent period could result in much higher dysfunction on the musculoskeletal system. Moreover, neuromuscular control and movement coordination are not completely developed by the time of adolescence (Quatman-Yates et al., 2011). Therefore, investigating relations between PA, adiposity, injury incidence and FM is important for the musculoskeletal health of the adolescents. Up to this date, few studies investigated the quality of movement and among the paediatric participants (Duncan et al., 2013; Duncan & Stanley, 2012; Mitchell et al., 2015; Molina-Garcia et al., 2020; Molina-Garcia, Migueles, et al., 2019). However, these studies had a small sample size, or recruited specific population (i.e. only obese participants) and did not include mid-adolescents. This makes it difficult to ascertain how the level of PA, adiposity, and injury might be associated with FM during this period. Without this, scientists, physical educationalists, and clinicians may make erroneous decisions by applying outcomes found on children onto mid-adolescents. To the best of author knowledge, there are no studies that examined the association between PA, adiposity, musculoskeletal injuries and FM in a large, random sample of mid-adolescents.

Research aims and questions

Looking altogether, studies that investigated FM in the pediatric population most often included preadolescent participants and were performed on a small number of children. To the best of the authors' knowledge, no studies have investigated relations between FM, PA and adiposity in a large representative sample of urban adolescents. Besides, there is a lack of studies investigating FM and future injury risks among average adolescent population.

Therefore, the main purpose of this doctoral thesis is to determine in which way are PA, adiposity, and injury related to the quality of movement patterns among adolescents. This dissertation is designed according to the Scandinavian model and it is divided into three distinct studies with related research questions and aims:

1) Is there a relationship between functional movement and PA in an urban adolescent population?

2) Is adiposity associated with the quality of movement patterns in the mid-adolescent period?

3) Can injuries be predicted via functional movement quality in a one-year period by using ML in a representative sample of urban athletic and non-athletic adolescents?

List of research studies

In order to answer above-mentioned scientific questions, the current doctoral thesis includes three studies that have been published:

1. **Karuc, J.**, Mišigoj-Duraković, M., Marković, G., Hadžić, V., Duncan, M. J., Podnar, H., & Sorić, M. (2020). Movement quality in adolescence depends on the level and type of physical activity. *Physical therapy in sport: official journal of the Association of Chartered Physiotherapists in Sports Medicine*, *46*, 194–203. https://doi.org/10.1016/j.ptsp.2020.09.006

2. **Karuc, J.**, Marković, G., Mišigoj-Duraković, M., Duncan, M. J., & Sorić, M. (2020). Is Adiposity Associated with the Quality of Movement Patterns in the Mid-Adolescent Period?. *International journal of environmental research and public health*, *17*(24), 9230. https://doi.org/10.3390/ijerph17249230

3. **Karuc, J.**, Mišigoj-Duraković, M., Šarlija, M., Marković, G., Hadžić, V., Trošt-Bobić, T., Sorić, M. (2021). Can Injuries Be Predicted via Functional Movement Screen in Adolescents? The Application of Machine Learning. *Journal of Strength and Conditioning Research*. Online ahead of print. (accepted on 28 December 2020).

LITERATURE REVIEW

Concepts and definitions of movement quality

To understand the definition of movement quality, first, we need to define the concept of movement competency. Movement competency is defined as the global movement patterns (i.e., locomotion, object control skills, or stability tasks) essential for the child motor development (Ahnert & Schneider, 2009; Stodden et al., 2008). An important aspect of the movement competency, and thus of motor development, is the qualitative component of the movement, often termed as the movement quality. Theoretically, movement quality can be defined similarly to the FM, where optimal movement quality presents an optimal range of motion, balance, and postural control of the specific movement patterns (Cook, 2011; Cook et al., 2006a, 2006b). Contrary, suboptimal movement quality is related to a compensatory movement pattern along the kinetic chain with associated loss in the range of motion, balance, and deficit in postural control of the specific movement pattern (Cook, 2011; Cook et al., 2006a, 2006b).

Movement quality assessment

Clinical measure of movement quality can be presented with the FM (Krause, 2014; Marques et al., 2017; Silva et al., 2019), most commonly assessed via Functional Movement Screen^{TM} (FMS^{TM}) (Cook et al., 2006a, 2006b). FMS^{TM} is a screening instrument designed for evaluation of mobility and stability of the seven functional movement patterns through seven tests (Cook et al., 2006a, 2006b): the deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise (ASLR), trunk stability push-up, and rotary stability. The importance of FM patterns has been discussed in previous studies (Cook et al., 2006a, 2006b; Krause, 2014; Marques et al., 2017; Silva et al., 2019) and they are considered as fundamental 'pillars' for the exhibition of complex movements (Cook et al., 2006a, 2006b), whereas DFM has been related to higher injury incidence (Bonazza et al., 2017; Garrison et al., 2015; Kiesel et al., 2014; Shojaedin et al., 2014) and potential movement pathologies in children with overweight (Duncan et al., 2013; Duncan & Stanley, 2012; Molina-Garcia et al., 2020). Incorporating FM patterns in exercise programs is critical for the optimal progress toward more complex movement skills (Cook, 2011; Cook et al., 2006a, 2006b).

According to previous research, two-hour education on using FMS™ is efficient to gain an optimal interrater and intrarater reliability (Smith et al., 2013). Each test is scored on a four-point scale (0–3), with higher scores indicating better movement quality. For each test, the highest score from the three trials was recorded. An overall composite score was calculated by summing the seven individual tests with a total FMS score of 21 according to standardized guidelines (Cook et al., 2006a, 2006b). FM can be quantitatively defined as the movement with a given score of 2 or 3 during the FMS™ procedure. Furthermore, a score of 1 was given when the participant was unable to perform movement due to the number of movement compensation present which reflects the DFM pattern (Cook, 2011; Cook et al., 2006a, 2006b). This means that score of 2 and 3 is an indicator of FM, whereas a score of 1 was an indicator of DFM for each of 7 individual FMS tests. Finally, when a participant reports pain during the movement testing, a score of zero is being recorded.

Movement quality during adolescent period of growth and maturation

The interest among researches and practitioners in studying FM and using the FMS™ across the various populations is constantly increasing (Abraham et al., 2015; Duncan et al., 2013; Duncan & Stanley, 2012a; Lester et al., 2017; Molina-Garcia, H Migueles, et al., 2019). Despite its importance and widespread usage, only a handful of studies have focused on FM in the pediatric population. Across the literature, it has been shown that age and maturity status could have a significant effect on the FMS score (Portas et al., 2016).

Several authors studied the relation between maturity status and movement quality during an adolescent period (Lloyd et al., 2015; Paszkewicz et al., 2013; Portas et al., 2016; Wright & Chesterton, 2019). Portas et al. (2016) studied the effect of maturity on FMS™ scores in 1163 elite adolescent soccer players aged between 8 to 18 years (Portas et al., 2016). The authors of this research found that post-peak height velocity athletes scored better on FMS tasks compared to those who were categorized in the peak height velocity group. The authors concluded that maturity has greatly affected movement quality (i.e. total FMS score) in elite adolescent soccer players. Another study investigated movement quality and maturity influence in sixty-six 8 to 14 years old adolescent athletes (Paszkewicz et al., 2013). Results of this research indicate that postpubescent children exhibit a better quality of movement compared with the prepubescent peers (total FMS score: 15.9 vs 14.3, respectively). Also, it has been shown that postpubescent children showed better quality of movement compared with the early-pubescent participants (total FMS score: 15.9 vs 14.5). This study confirmed that the FMS™ diagnostic tool has the power to discriminate between maturity levels during the pubertal growth cycle.

Sexual dimorphism in the quality of movement during adolescence

During the adolescent period, there are evident sex differences in the performance of movement quality. The literature suggests that sexual dimorphism exists in specific and general movement patterns (Bentham et al., 2017; Duncan & Stanley, 2012; García-Pinillos et al., 2018; Lester et al., 2017; Paszkewicz et al., 2013; Pfeifer et al., 2019). More specifically, during the adolescent period, girls exhibit better movement quality compared to boys (Bentham et al., 2017; Duncan & Stanley, 2012; García-Pinillos et al., 2018; Lester et al., 2017; Paszkewicz et al., 2013; Pfeifer et al., 2019). Also, sexual dimorphism in movement quality is evident in both athletic and average adolescent populations (Bentham et al., 2017; Duncan & Stanley, 2012; García-Pinillos et al., 2018; Lester et al., 2017; Paszkewicz et al., 2013; Pfeifer et al., 2019). In addition, girls perform better on FMS™ movement tasks that require flexibility and mobility of the joins (Duncan et al., 2013; Mitchell et al., 2015; O'Brien, 2018; Pfeifer et al., 2019) while boys are better at tests that challenges trunk stability and upper-body strength (Abraham et al., 2015; Duncan et al., 2013; Duncan & Stanley, 2012; García-Pinillos et al., 2018; Mitchell et al., 2015; O'Brien, 2018; Paszkewicz et al., 2013).

Concepts and definitions of physical activity

PA can be defined as: “Any body movement generated by the contraction of skeletal muscles that raises energy expenditure above resting metabolic rate. It is characterized by its modality, frequency, intensity, duration, and context of practice” (Caspersen et al., 1985), while physical inactivity relates to the following: “Represents the non-achievement of physical activity guidelines” (Thivel et al., 2018). There are three components that define a total volume of PA: frequency, duration, and intensity. Frequency is defined as the number of movements per day, duration presents minutes spent in a particular activity, while intensity represents an effort to perform a movement. In children, physiological, behavioral, socio-cultural, and physical environmental factors can influence the level of PA (Taylor & Sallis, 1997).

Physical activity assessment in adolescence

PA can be evaluated via different measurement techniques. Direct calorimetry presents the golden standard in the evaluation of the level of energy expenditure. Also, the method of doubly-labeled water is being used in the control settings. Although these techniques can be very useful in the control settings, they are not applicable for population-based and epidemiological studies. In population-based research, objective estimation of PA level is often being used, which can be accessed via accelerometers, heart rate monitors, and multi-sensors. However, in epidemiological research, PA is often assessed with subjective methods which include questionnaires, interviews, and diaries. There are many instruments (i.e. questionnaires and surveys) that are used in the literature. According to the literature, the Physical Activity Questionnaire (PAQ-C/PAQ-A), Youth Risk Behaviour Surveillance Survey (YRBS), and Teen Health Survey received support and validation from the expert group and the scientists (Biddle et al., 2011). PAQ-C and PAQ-A are two different versions of the PA questionnaire with two versions of this scale, one intended for children (C) aged 8-14 (Crocker et al., 1997), and the other for adolescents (A) aged 14-20 (Kowalski et al., 1997). The PAQ-C assesses the level of PA in children by recalling the activities in the last week. This questionnaire has nine items and offers a list of activities and frequency of participation. Frequency of participation is measured on the five-point scale: 1) no; 2) one to two times per week; 3) three to four times per week; 4) five to six times per week; and 5) seven times per week or more (Crocker et al., 1997). PAQ-A is a modified version of PAQ-C intended for high school children. This questionnaire consists of eight questions regarding PA during school time. The questions within the PAQ-C are the same as for the PAQ-A, except that the item about PA during recess is removed (Kowalski et al., 1997). YRBS (Brener et al., 1995; Caspersen, 2000) consists of 5 items for both moderate PA (MPA) and vigorous PA (VPA) as well as items that evaluate sedentary behavior. Teen Health Survey is a modified version of the YRBS instrument with two items that require answers about PA level in the adolescent population. Evidence suggests that there is a moderate-to-good association between Teen Health Survey with other accelerometry-based instruments (Prochaska et al., 2001). In addition to the aforementioned instruments, high validity questionnaires that are based on strength of statistical value are School Health Action, Planning, and Evaluation System (SHAPES) and Finnish Twin Cohort Study questionnaire. Two above-mentioned questionnaires are commonly used to assess PA in children and adolescents (Wong et al., 2006; Biddle et al., 2011).

SHAPES questionnaire is constituted of 45 multiple-choice questions and was specifically designed for repeated school-based surveys. Two items request a 7-d recall of VPA and MPA, respectively. VPA is described as “jogging, team sports, fast dancing, jump-rope, and any other PA that markedly increased your heart rate and made you breathe hard and sweat”, while MPA was defined as “lower intensity physical activities such as walking, and riding a bike”. Responses are provided by indicating the number of hours and 15-min increments that each type of PA was performed for each day of the previous week. Therefore, the intensity, duration, and frequency of PA were documented, and the total volume of PA was calculated. The average time during the day spent while performing moderate-to-vigorous PA (MVPA) can be calculated by summing the weekly time spent performing VPA and MPA divided by 7. Wong et al. (2006) reported that MVPA estimated using the SHAPES questionnaire correlated moderately with the values of the accelerometer device ($r = 0.44$). The results of this PA questionnaire can be comparable with other instruments for adolescents as prior reliability research using the SHAPES questionnaire showed moderate agreement for moderate and vigorous PA (Wong et al., 2006).

Physical activity during childhood and adolescence

Insufficient PA is related to many noncommunicable diseases, shortened life expectancy (Department of Health & Human Services, 2018), leading to a large economic burden and global health problem (Ding et al., 2016). Recent reports have shown that inactive children are exposed to increased metabolic and cardiovascular risk (Janssen & LeBlanc, 2010). Several studies point to the positive effects of regular PA on physical, cognitive, and mental health in children (Janssen & LeBlanc, 2010).

In addition to the negative consequences of physical inactivity, low levels of PA have been related to suboptimal proprioception (Ribeiro & Oliveira, 2011) and possible decreases in neuromuscular innervation. More importantly, evidence shows that extremely low levels of PA can lead to loss of muscle volume, physiological cross-sectional area, loss of fascicle length, changes of pennation angle and muscle strength as well as deficits in motor control (Campbell et al., 2013) which can potentially lead to suboptimal movement quality (Duncan et al., 2013; Duncan & Stanley, 2012). According to the recently published and meta-analysis, PA and physical education improves classroom behaviors and academic achievement, mainly language-related and mathematics-related skills, and reading in children and adolescents (Alvarez-Bueno et al., 2017).

Many factors can hinder engagement in PA. Risk of the injury is the most common factor that can prevent a physically active lifestyle (Janssen & LeBlanc, 2010). On the other hand, physically non-active children are at higher risk for injury incidence (Bloemers et al., 2012), although the opposite has also been reported in an older study (Janssen & LeBlanc, 2010). Low level of PA is related to suboptimal proprioception (Ribeiro & Oliveira, 2011), which can then lead to less than optimal movement patterns.

According to the ecological approach to health behavior (Sallis et al., 2000), there are five groups of factors that play a significant role in PA: 1) demographic and biologic factors; 2) psychological, cognitive, and emotional factors; 3) behavioral attributes and skills factors; 4) social and cultural factors; and 5) physical environmental factors. Among the demographic and biological factors, evidence suggests that age and sex are the most significant correlates of PA in adolescence (Ammouri et al., 2007; Higgins, Gaul, et al., 2003). In general, adolescent boys are more physically active compared to adolescent girls (Ammouri et al., 2007; Higgins, et al., 2003). Also, there is an inverse association between the level of PA and age – as adolescents are getting older they are less physically active (Ammouri et al., 2007; Kristjansdottir & Vilhjalmsson, 2001; Neumark-Sztainer et al., 2003; Voorhees et al., 2005). Among other demographic and biological factors, socio-economic status (SES) and parents' education level also play an important role in adolescent PA status. Parents with higher education and families with higher SES have children who are more physically active compared to lower-income families and parents with lower education (Tammelin et al., 2007; La Torre et al., 2006).

Psychological, cognitive, and emotional factors play an important role concerning the level of PA during adolescence. On the other hand, the literature suggests that there are several important barriers that could prevent adolescents from being physically active. These barriers are: lack of time, too much spent on homework, tiredness, and lack of motivation (Chang, 2004; Robbins et al., 2003). Among behavioral attributes and skills factors related to PA, smoking and alcohol consumption are most important. Studies have shown that consumption of smoking and alcohol is negatively related to the level of PA among adolescents. Social and cultural factors include social, parental, and peer support related to physical exercise and activity. It has been shown that social support is positively related to the PA level in the adolescent period (Ammouri et al., 2007; Chang, 2004). Proximity, cost, facilities, and safety are the most important physical environmental factors among adolescents with low-SES.

According to the World Health Organization (WHO) (2020) recommended levels of PA for children aged between 5 to 17 suggest that children should accumulate at least 60 minutes of moderate-to vigorous-intensity physical activity (MVPA) per day (World Health Organization, 2020). Also, the WHO suggests that children should perform strength-related exercises at least 3 times per week (World Health Organization, 2020).

Concepts and definitions of adiposity

According to the Merriam-Webster dictionary, the medical definition of adiposity can be defined as the quality or state of being fat while Bays et al. (2013) suggested the following definition: ‘‘ ‘Adiposity’ is defined as the degree of body fat accumulation and is generally used in the present work to denote excess body fat.’’ (Bays et al., 2013).

Another term commonly used for adiposity is obesity. Similar to the above-mentioned definition of adiposity (Bays et al., 2013), Ayer et al. (2015) defined obesity as: “excess of body fat which confers an increased risk of adverse health outcomes.”(Ayer et al., 2015). However, obesity is defined by cut-off values rather than direct measurement of body fat, as Bayes et al. (2013) stated: “ ’obesity’ is mostly defined as per established classification metrics relative to BMI.” (Bays et al., 2013). Therefore, in the literature, to distinguish between children with normal weight and children with overweight or obesity, age and sex-specific BMI cut-off points proposed by the International Obesity Task Force criteria are being widely used (Cole et al., 2000). Children with BMI below the age- and gender-specific 85th percentile are defined as children with normal weight. Children and adolescents with BMI equal to or above the age- and gender-specific 95th percentile are categorized into a group of children with obesity. Children with BMI equal to or above the 85th percentile – but below the 95th percentile – are categorized into a group of children with overweight.

On the other hand, the definition of obesity based on body fat is still arbitrary. Across the literature, the most commonly used cut-off values that will determine excess body fat in male adolescents are 25–30% (for adolescents aged 10–15 years), and 20–25% (for adolescents aged above 18 years) (Rodríguez et al., 2004). However, among adolescent girls, the most common cut-off values that will determine excess body fat ranges between 30 to 35 % (Rodríguez et al., 2004).

Body fat assessment

Body fat can be measured and estimated via different methods and techniques. Common body fat estimation methods include underwater weighing, air displacement plethysmography, dual-energy X-ray absorptiometry (DXA), bioelectrical impedance analysis (BIA), skinfold thickness, waist circumference (WC), hip circumference (HC), waist-to-height ratio (WHtR), and body mass index (BMI) (Ayer et al., 2015; Schwandt, 2011).

Based on Boyle's law, air displacement plethysmography employs the reciprocal relationship between pressure and volume in order to calculate body volume. After body volume is calculated, body composition is evaluated from body density (Brozek et al., 1963; McCrory et al., 1998; Azcona, 2006). It has been shown that air displacement plethysmography is a reliable method for assessing body composition in the pediatric population (Ittenbach et al., 2006). Another method that is commonly used is DXA. DXA was originally developed to measure bone mineral mass using ionising radiation. DXA uses an x-rays system and with the algorithmic approach, the percentage of specific soft tissue for the whole body can be evaluated (e.g. fat mass) (Wells & Fewtrell, 2006). BIA measures body composition based on the impedance of the body to the electric current. According to the standard measurements, electrodes are positioned on the wrist and ankle joint. Based on the given bioelectric signals, this technique estimates total body water, and thus body fat (Wells & Fewtrell, 2006). Apart from the laboratory techniques, in clinical practice skinfold thickness measurements are often used. Skinfold thickness measurements evaluate the amount of subcutaneous fat depots (Wells & Fewtrell, 2006). Studies have been shown that skinfold thickness is a better predictor of adiposity than BMI in the adolescent population (Nooyens et al., 2007).

WC is a valid indicator of central fatness and represents a valid indicator of lipid profile (Wells and Fewtrell, 2006). It has been shown that WC adolescents correlate with metabolic syndrome and fat deposits in young adults (Spolidoro et al., 2013). On the other hand, BMI is the most widely used measure of fatness in population-based research. However, BMI as a measure of fatness has its strengths and limitations and clinicians and researcher need to be cautious when using BMI as the measure of adiposity. Freedman et al. pointed out that "when using BMI-for-age to estimate body fat percentage among adolescents, the estimation is poorest at about the 85th percentile of BMI". However, the accuracy of body fat percentage prediction based on BMI values improves at higher levels of BMI-for-age (Freedman et al., 2007). In the validation study done by Pietrobelli et al. (1998), BMI was validated as the measure of adiposity. The results of the aforementioned study support the use of BMI as the indicator of adiposity in the adolescent population (Pietrobelli et al., 1998). According to Dietz et al. (1998), BMI presents "a reliable measure with reasonable measurement and clinical validity in children and adolescents". Therefore, BMI can be effectively used as a measure of adiposity for research in large-scale studies (Dietz et al., 1998).

Due to its efficacy in epidemiological studies, anthropometric measurements (e.g. circumferences, weight, longitudinal measurements of a skeleton) are used mostly for body fat estimation. The most commonly used measures include WC, BMI, and waist-to-height ratio (WHtR). According to the literature, WHtR presents the best indicator of central adiposity in an adolescent population (Schwandt, 2011). Evidence suggests that WHtR (≥ 0.5) combined with high waist circumference (≥ 90^{th} percentile) predict a near to four-fold increase risk for cardiovascular diseases. Also, evidence demonstrates that waist circumference (≥75th percentile) is related to metabolic syndrome in children and adolescents (Bitsori et al., 2009).

Adiposity during childhood and adolescence

Childhood obesity presents one of the largest public health problems with serious long-term health consequences. In the last three decades prevalence of childhood obesity increased by 47% worldwide (Ayer et al., 2015). Children with obesity have a higher risk of developing diabetes type 2, cardiovascular diseases, cancer, and musculoskeletal disorders later in life (Krul et al., 2009; Merder-Coşkun et al., 2017; Weihrauch-Blüher et al., 2019). Childhood overweight has been associated with higher insulin and lipid levels in the period of young adulthood (Bridger, 2009). Recent reports show that obesity in adolescence is associated with elevated blood pressure, atherosclerosis, atherogenic dyslipidemia, metabolic syndrome, type 2 diabetes mellitus, cardiac structural and functional changes, and obstructive sleep apnea (Raj, 2012). Also, evidence suggests that children with obesity are more likely to stay obese during the adult age as well (Singh et al., 2008).

Compared with children with normal weight, children with overweight have poorer academic performance (Wu et al., 2017). Indeed, several researchers have shown a negative relationship between obesity in adolescence and academic performance (Wu et al., 2017). Besides poorer academic performance, children with overweight show a deficit in working memory (Wu et al., 2017). Also, evidence shows that children with overweight have poor mental health (Rankin et al., 2016). Results from the recent review suggest that childhood overweight and obesity was associated with depression, poorer perceived lower scores on health-related quality of life, emotional and behavioral disorders, and self-esteem during childhood (Rankin et al., 2016).

The main risk factors for childhood obesity include physical inactivity, sedentary behavior, and dietary intake (Davison et al., 2001). It has been shown that biological factors, mainly sex and genetics, play important role in adolescent obesity (Shah et al., 2020). According to the evidence, there is a higher prevalence of obesity in boys compared with girls (Shah et al., 2020). It has been discussed that these sex differences may arise due to sex steroid hormones which are related to sexual dimorphism in body composition among a pediatric population (Shah et al., 2020). Although sex plays important role in childhood obesity, on the other hand, the contribution of genetics in childhood obesity is small, but still relevant (Anderson et al., 2006). In addition to the biological factors, the literature suggests that family factors, such as dysfunctional parenting style and parents' lifestyles are essential components for unhealthy beahviour and bad eating habits (Sahoo et al., 2015).

Also, one of the most significant contributors to obesity in adolescence is sedentary behavior (Sahoo et al., 2015). Environmental and socio-cultural factors are also potential causes of obesity in adolescents (Sahoo et al., 2015). School policies and demographics, along with the extensive television viewing and accumulation of sedentary time add to physical inactivity which can play a significant role in developing obesity (Sahoo et al., 2015). Psychological factors such as depression and anxiety, lower self-esteem, body satisfaction play a significant role in adolescent obesity. However, the above-mentioned relationship between obesity and psychological disorders are not unidirectional – they could be cause and consequence of obesity (Sahoo et al., 2015). In addition to the aforementioned, researches have been shown that eating disorder symptoms and emotional problems are common in the adolescent obese population (Sahoo et al., 2015).

Amongst the above-mentioned risks of paediatric obesity, musculoskeletal disorders with associated biomechanical and health impact have been least studied systematically. According to the most recent umbrella review which investigated the association between adiposity and physical function in children with obesity, few published systematic reviews drew attention to the phenomena of the biomechanics of childhood obesity (Tsiros et al., 2020). Indeed, only one review pointed to the negative influence of excess weight on movement biomechanics among children with possible long-term consequences on musculoskeletal health (Molina-Garcia, Migueles, et al., 2019). According to the recent evidence, three inter-related clinical and biomechanical components are compromised in children with overweight: (1) body posture (Araújo et al., 2017; Brzeziński et al., 2019; Jankowicz-Szymańska et al., 2019; Lonner et al., 2015; Maciałczyk-Paprocka et al., 2017), (2) gait biomechanics (Catan et al., 2020; Molina-Garcia et al., 2019), and (3) movement competence (Duncan et al., 2013; Duncan & Stanley, 2012; Pill & Harvey, 2019; Tsiros et al., 2020). This could be concerning since the number of children with overweight and obesity is still increasing around the globe (Di Cesare et al., 2016).

Concepts and definitions of musculoskeletal injury

There are many definitions of musculoskeletal injuries and are often difficult to compare. One of the most common definition of injury used in the research is: “tissue damage due to a transfer of external energy to the body” (Schuh-Renner et al., 2019). However, the aforementioned definition is partially limited because it does not take into consideration more important criterion for injury to be established, that is, the length of absence of PA. On the other hand, according to the definition proposed by Patel et al. (2017) and the Centers for Disease Control and Prevention (CDC), the injury was defined as follows: “ sport injuries were defined as those: (I) resulting from participation in an organized high school athletic practice or competition, (II) requiring medical attention from a certified athletic trainer or a physician, and (III) restricting the athlete’s participation for 1 or more days beyond the day of injury” (Centers for Disease Control and Prevention, 2006; Pate et al., 2017). The severity of the injury can be defined as one which precluded participation in PA for at least one week (Philp et al., 2018). The importance of this kind of definition that is related to health status and PA is well discussed and supported in a research work done by van Mechelen (van Mechelen et al., 1992) who points out that “definition of injury should be based on a concept of health other than that customary in standard medicine”. The definition of musculoskeletal injury used in this doctoral thesis is similar to the definition of the National Athletic Injury Registration System (NAIRS) in the US., where the main criteria for injury to be established is the length of incapacitation/absence of PA expressed in a number of days (time-loss injury) (Alles et al., 1979). Therefore, the explicit definition of an injury in this thesis was defined as: “PA-related musculoskeletal injury, which included minor to severe injuries”. The most commonly used parameter of injury severity is time loss from game or practice (Ekegren et al., 2016). One of the most common classifications suggests several categories for time loss injury indicator: 1) non-reportable; 2) no time lost, 3) one to seven days lost (minor); 3) eight to twenty-one days lost (moderate), 4) more than 21 days lost, and 5) severe injury resulting in permanent disability (Ekegren et al., 2016). In addition to the aforementioned, there are other determinants that can indicate the severity of the injury, such as cost of treatment, duration of rehabilitation, nature of injury, etc. (Ekegren et al., 2016).

Musculoskeletal injury diagnostics and epidemiological assessment

Musculoskeletal injuries in the researches can be diagnosed with physical examination performed by a qualified medical expert, confirmed with the different radiological techniques, or can be assessed via validated questionnaires. In epidemiological studies, questionnaires are most commonly used to assess injury status among different populations. Gabbe et al. reported the perfect agreement (k = 1.00, 95% CI 1.00 to 1.00) between retrospective and prospective records when subjects were asked whether or not an injury had occurred during the one-year period (yes/no answer) (Gabbe, et al, 2003). The questionnaire used in this thesis provided information about the nature of injuries such as the number of injuries, injured body region, and the context of an injury (during an activity or not and during which activity injuries had occurred). Although recall accuracy decreases as the number of detail increases, the validity of self-reported injury (with yes/no answer) in the12-month period has shown to be perfect (Gabbe et al, 2003).

Musculoskeletal injuries in the adolescent period

Musculoskeletal injuries and conditions represent a major public health problem, with significant social, economic, and health consequences (Mock & Cherian, 2008; Rosenfeld et al., 2018). Indeed, impaired proprioception, muscle weakness, poor balance and joint instability, limited range of motion, and persistent pain have been frequently observed following musculoskeletal injury (Abassi et al., 2019; Friden et al., 1997; Friel et al., 2006; Gribble et al., 2016; Hertel et al., 2001). A recently published systematic review has shown that changes in the range of motion occurring during the progress through adolescence and growth spurts may lead to an increase in injury incidence as well (Storm et al., 2018). It has been repeatedly shown that adolescence presents the most sensitive period to higher vulnerability to injury (Dowd et al., 2002; Pickett et al., 2002; Walsh & Jarvis, 1992; Williams et al., 1996). Therefore, it is of crucial importance that the hierarchy of responsibility for injury incidence is well established in adolescent population (Emery et al., 2006). In adolescence, various factors can contribute to higher injury risk such as previous injury, sports participation, high BMI, total body fat and others (Emery, 2015; Emery &

Tyreman, 2009; Jespersen et al., 2014). Also, the risk of the injury is the most common factor that can prevent a physically active lifestyle (Janssen & LeBlanc, 2010). On the other hand, physically non-active children are at higher risk for injury incidence (Bloemers et al., 2012), although the opposite has also been reported in an older study (Janssen & LeBlanc, 2010). Also, there are specific aspects related to growth and development which contribute to the risk of PA-related musculoskeletal injuries (Patel et al., 2017) which include: height and weight, muscle growth and strength, motor skills and performance, body composition, flexibility, growth cartilage, bone structure, and psychological maturity. Patel et al. (2017) pointed out that "the immature growth plate is vulnerable to stress injury", and that "increase in the rate of height and weight during adolescence contribute to increasing in momentum and force during a collision with another athlete" which can predispose the adolescent athlete to higher injury incidence. Also, since in adolescence relative weakness of growing bones is present, there is increased injury risk for tendons, ligamentous, and bony avulsions (Patel et al., 2017).

Concerning time from injury incidence and duration of present injury, we can differentiate acute trauma (e.g. catastrophic trauma), subacute injury, and overuse injuries (chronic state of injury). Overuse injuries are most common among children and adolescents (Ekegren et al., 2016). Definition of overuse injury can be defined as: "An overuse injury is a result of repetitive and excessive stress from physical activity applied to normal musculoskeletal tissues and failure of normal adaptation of the tissue" (Patel et al., 2017). The sudden increase in the intensity, duration, and volume of physical activity, poor conditioning, insufficient sport-specific training, poor training techniques, and inappropriate equipment are considered as the relatively more consistently associated factors that contribute to overuse musculoskeletal injuries in adolescents. On the other hand, relatively less consistently associated factors include anatomic variations, especially in lower extremities, hard-playing surface, stress to the growth cartilage, differential growth between bones and musculotendinous structures, decreased musculotendinous flexibility, and presence of associated neuromuscular conditions (Patel et al., 2017; Caine et al., 2008; Rosendahl et al., 2016; DiFiori et al., 2014). Also, injury can be diagnosed by type of exposure. Sprain or strain injuries are most frequent, while contusions and fractures are less common among injured adolescent athletes (Patel et al., 2017).

The location of the injury is important for precise and valid diagnosis. Injured body location depends on various factors. Mainly, injured body location depends on the type of sport activity and specific movement patterns present in a specific activity. For example, in contact sports (wrestling, football, hockey), the shoulder is frequently injured (i.e. clavicular fracture); throwing athletes tend to injure elbow joint (i.e. stress injury, flexor tendinopathy, ulnar collateral ligament injury); while high-risk sports may predispose adolescent athletes to a higher risk for spine injuries (Scheuermann disease are common in gymnastics, rowing, weightlifting; intervertebral disk herniation at L4/L5/S1 is found among football, diving, skiing, gymnastic athletes) (Patel et al., 2017).

Relationship between injury incidence and movement quality in adolescent period

There is a growing body of evidence that investigate movement quality among athletic youth. Several studies suggested functional movement quality, measured via FMS^{TM}, as one of the potential predictive factors of injury in young and adult athletes, while some other studies reported the opposite. The most commonly used diagnostic tool to assess the risk of injury via movement quality is the FMS^{TM} (Cook et al., 2006a, 2006b) .

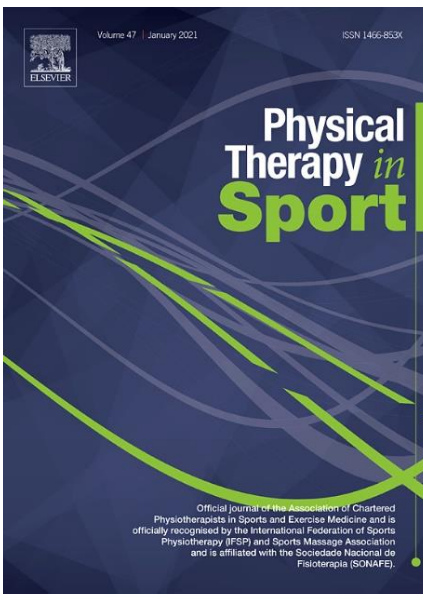
In the past few years, several articles (Moran et al., 2017; Philp et al., 2018; Pollen et al., 2018; Warren et al., 2018) have seriously undermined the predictive validity of the FMS among various populations (adults, athletes, firefighters, etc.). Emphasizing that although the reliability of the test is excellent (Warren et al., 2018), it is not enough as FMS does not demonstrate the properties essential to be considered as a measurement scale and has neither measurement nor predictive validity (Philp et al., 2018). Previous studies investigating the association between FMS and injury occurrence have covered mainly the athletic adolescent population. For example, a study that included 119 male and female college basketball players who performed FMS preseason and postseason did not show significant discriminatory power of FMS to predict injury occurrence and have reported AUC of 0.43–0.49 (Bond et al., 2019). Furthermore, in a study where 27 injury-free adolescent cricket players were prospectively followed over a season, after performing a preseason FMS screening, the authors concluded that the composite FMS score is a poor predictor of in-season injury (Martin et al., 2011). Finally, in 167 high-school athletes who were monitored for injury during a single season only, in-line lunge scores were significantly higher for injured players, suggesting that FMS should not be used of overall injury predictions in high school athletes. Although some studies have reported the limited value of FMS^{TM} to predict injury across different populations, some earlier studies showed that the total FMS score below 14 raises the risk of injury among athletes.

Kiesel et al. (2007) were first who reported that FMS^{TM} cut-off score ≤14 can successfully predict injury occurrence among American professional football players (specificity=0.91; sensitivity =0.54) (Kiesel et al., 2007). In the similar study, Kiesel et al. examined 238 American professional football players and revealed that athletes with at least one asymmetry presented in individual FMS^{TM} tasks have a higher risk for injury incidence compared to athletes without injury (Kiesel et al., 2014). This study also confirmed previous findings where athletes who scored ≤ 14 points on FM^{TM} testing procedures have a higher risk of injury occurrence. Another study, done by Shojaedin et al. examined 100 university-level athletes (age of 22.56 ± 2.99 yo) and the relationship between FMS with injury risk (Shojaedin et al., 2014). This study determined that athletes have close to a five times greater chance of suffering a lower extremity injury if they scored less than 17 points on the FMS testing. Garrison et al. aimed to determine the association between pre-season FMS^{TM} scores and the development of injury in a population of collegiate athletes 160 collegiate athletes. Athletes with an FMS™ composite score at 14 or below combined with a self-reported past history of injury were at 15 times increased risk of injury (Garrison et al., 2015). Looking altogether, there is conflicting evidence for the FMS^{TM} injury prediction value. Also, there are many studies performed on athletic adolescents, however, there is a lack of evidence for FMS^{TM} injury prediction value in the average adolescent population. Therefore, prediction of injury incidence needs to be established for the average adolescent population as well.

ORIGINAL STUDIES

Study 1: Movement quality in adolescence depends on the level and type of physical activity

Karuc, J., Mišigoj-Duraković, M., Marković, G., Hadžić, V., Duncan, M. J., Podnar, H., & Sorić, M. (2020). Movement quality in adolescence depends on the level and type of physical activity. *Physical therapy in sport: official journal of the Association of Chartered Physiotherapists in Sports Medicine*, *46*, 194–203. https://doi.org/10.1016/j.ptsp.2020.09.006



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Original Research

Movement quality in adolescence depends on the level and type of physical activity

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A R T I C L E I N F O

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A B S T R A C T

Objectives: This study examined the relationship between functional movement and physical activity (PA) levels in adolescents.
Design: Cross-sectional study.
Setting: This research is a part of the CRO-PALS longitudinal study conducted in a random sample of adolescents in Zagreb at the Faculty of Kinesiology, University of Zagreb, Croatia.
Participants: Seven hundred and twenty-five adolescents aged between 16 and 17 years were included.
Main outcome measure: Total Functional Movement Screen score (total FMS score).
Results: After adjusting for age, body fat and SES, both VPA and MVPA showed minor but significant effects on total FMS score among girls (β=0.011, p= 0.001, β=0.005, p=0.006, respectively), but not in boys (β =0.004, p=0.158; β =0.000, p=0.780). Regarding PA type, volleyball and dance improved total FMS score (β =1.003, p=0.071; β=0.972, p=0.043, respectively), while football was associated with lower FMS score (β = -0.569, p=0.118).
Conclusion: Results suggest that the PA level is positively associated with the functional movement in adolescent girls, but not in boys, where the type of PA moderates these associations. Therefore, functional movement patterns incorporated into physical education curriculum could be beneficial to the musculoskeletal health of the children.

1. Introduction

Insufficient physical activity (PA) is related to many noncommunicable diseases, shortened life expectancy (Department of Health & Human Services, 2018), leading to a large economic burden and global health problem (Ding et al., 2016). Recent reports have shown that inactive children are exposed to increased metabolic and cardiovascular risk (Janssen & Leblanc, 2010). Several studies point to the positive effects of regular PA on physical, cognitive, and mental health in children (Janssen & Leblanc, 2010). In addition to negative consequences of physical inactivity, low levels of PA have been related to suboptimal proprioception (Ribeiro & Oliveir, 2011) and possible decreases in neuromuscular innervation. More importantly, evidence shows that extremely low levels of PA can lead to loss of muscle volume, physiological cross-sectional area, loss of fascicle length, changes of pennation angle and muscle strength as well as deficits in motor control (Campbell et al., 2013) which can potentially lead to dysfunctional movement (Duncan & Stanley, 2012; Duncan, Stanley, & Leddington Wright, 2013). Dysfunctional movement patterns are defined as compensatory movement patterns in the kinetic chain which are caused by loss of motor control and deficit in mobility and stability of joints (Cook, 2011). In addition, dysfunctional movements can limit exhibition of high intensity PA and may lead to acute or chronic injury (Garrison, Westrick, Johnson, & Benenson, 2015; Kiesel, Butler, & Plisky, 2014; Shojaedin, Letafatkar, Hadadnezhad, & Dehkhoda, 2014). Likewise, some experts believe that dysfunctional movement patterns may lead to structural pathological deformities (Duncan et al., 2013; Duncan & Stanley, 2012; Frank, Kobesova, & Kolar, 2013). Bringing this together, low level of PA along with the dysfunctional movement patterns could impact a person's health.

In contrast, optimal functional movement implies optimal motor control, proprioception, adequate mobility, and stability of the joints and body regions involved in a specific movement (Cook, 2011; Cook, Burton & Hoogenboom, 2006a, 2006b). It has been shown that exercises that include stability and motor control components lead to better functional movement (Mahdieh, Zolaktaf, & Karimi, 2020). Also, optimal functional movement patterns are prerequisites for performing high-intensity PA and exercises (Cook, 2011). Therefore, practicing functional movement patterns is of fundamental importance for the development of complex motor skills. The most commonly used diagnostic tool to assess functional movement quality is the Functional Movement Screen (FMS™) (Cook et al., 2006a; Cook et al., 2006b). The FMS™ is a screening tool that evaluates the quality of functional movement by examining seven fundamental movement patterns through the following seven tests: the deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise (ASLR), trunk stability push-up, and rotary stability. An overall composite score noted as a total FMS score is calculated by summing the values of the seven FMS™ tests. In this way, lower scores obtained on FMS™ testing indicate less than optimal functional movement (e.g. dysfunctional movement) (Cook et al., 2006a; Cook et al., 2006b). Studies have shown that lower total FMS scores are related to higher injury risk (Bonazza, Smuin, Onks, Silvis, & Dhawan, 2017; Krause, Schütz, Taylor & Doyscher, 2014). Furthermore, it has been shown that FMS™ can successfully predict injury occurrence among athletes (Garrison et al., 2015; Kiesel et al., 2014; Shojaedin et al., 2014), while other studies indicate the opposite (Bardenett et al., 2015; Dorrel, Long, Shaffer, & Myer, 2015; Dossa, Cashman, Howitt, West, & Murray, 2014).

In addition to the consequences of dysfunctional movement, the development of dysfunctional movement patterns through adolescence can cause even greater and negative health consequences as inter-segmental and inter-limb coordination, neuromuscular and postural control are not fully matured by the time of adolescence (Quatman-Yates, Quatman, Meszaros, Paterno, & Hewett, 2012). Duncan and Stanley (Duncan & Stanley, 2012) pointed out that developed dysfunctional movement in childhood and adolescence can lead to potential orthopaedic abnormalities in later life. Therefore, acquired optimal functional movement patterns during childhood and adolescence need to be sustained by proper training system and training methods during the adulthood. From the neurodevelopmental standpoint (Frank et al., 2013), the source of dysfunctional movement patterns can be twofold (Mahdieh et al., 2020): *1) lack of PA and exercise, and 2) repetitive subcortical exhibition of the compensatory movement patterns* in the sensitive growth period. Therefore, investigating how PA influence functional movement during childhood and adolescence needs special attention.

The interest among researches and practitioners in studying functional movement and using the FMS™ across the various populations is constantly increasing (Abraham, Sannasi, & Nair, 2015; Duncan et al., 2013; Duncan & Stanley, 2012; Lester et al., 2017; Molina-Garcia et al., 2019).

Despite its importance and widespread usage, only a handful of studies have focused on functional movement in the pediatric population (Abraham et al., 2015; Duncan et al., 2013; Duncan & Stanley, 2012; Lester et al., 2017; Molina-Garcia et al., 2019). To date, only two studies examined the relationship between PA and functional movement in children (Duncan & Stanley, 2012; Molina-Garcia et al., 2019), both reporting that a higher level of PA is positively related to total FMS score. While such research is welcome, these aforementioned studies were performed on a small number of conveniently selected children and included only preadolescents. This limits the conclusions that can be drawn in regard to the importance of PA on functional movement in the adolescent population. Therefore, understanding how PA impacts functional movement during adolescence is important and the first step to targeting interventions effectively for health benefit. In particular, to the authors' knowledge, there are no studies that investigated the relationship between PA level and functional movement in the general adolescent population. Therefore, the aim of this research was to examine the relationship between PA and functional movement in an urban adolescent population. We hypothesized that a higher PA level will be positively related to the total FMS score in the population of urban adolescents.

2. Methods

2.1. Participants

All measurements for this investigation were performed in the spring 2015 as part of a longitudinal four-year study (CRO-PALS) conducted from 2014 to 2017 in Zagreb (Croatia). Details on the sampling and procedures of the study have been described elsewhere (Štefan, Sorić, Devrnja, Podnar, & Mišigoj-Duraković, 2017). In brief, using stratified two stage random sampling procedures (school level and class level), 86 secondary schools were stratified by type: grammar schools/ vocational schools/private schools (Zagreb). During the first stage of random selection, 13 public (8 vocational and 5 grammar schools) and 1 private school (grammar school) were selected, considering the proportion of different types of schools and the average number of students per school of around 1500. Then, in the second stage of randomization, half of the first grade classes in each of the selected schools were randomly selected. At the end, 1408 students from 52 classes were enrolled, thus 64% agreed to participate (n = 903) (Štefan et al., 2017). Post-hoc power analysis for level-two hierarchically structured data (Browne, Golalizadeh Lahi, & Parker, 2009) for the main predictor (i.e. VPA) revealed that in order to achieve the power of 0.8 with alpha level set at 0.05, the optimal number of classes with the cluster size of one should be 42. The fact that this study included 52 classes with the cluster size ranging from 1 to 18, thus indicates that it was adequately powered to detect associations of the main predictors with the primary outcomes. One hundred and twenty-five participants were unavailable on the day of testing or did not complete the FMS screening and PA assessment. As a consequence, we included data from 778 adolescents (mean age ± SD = 16.6 ± 0.4 years).

All the participants had to meet certain criteria for the medical doctor to perform the screening process, specifically: 1) not having any pain during the movement screening and 2) not having an acute medical condition that precluded FMS™ testing (neurologic disorders or serious orthopaedic trauma such as bone fractures or complete muscle ruptures). Accordingly, 53 participants were excluded. Therefore, the total number of participants that was analyzed was 725 adolescents (girls, n = 366; boys, n = 359). The flowchart of the included participants is shown in Fig. 1.

The Ethics Committee of the Faculty of Kinesiology at the University of Zagreb (Croatia) approved the procedures of this study (No: 1009-2014), which was executed according to the Declaration of Helsinki. The written consent of the parents or legal guardians of the children was ensured once they have been informed of the study aims, the protocol, and the possible discomforts they might encounter.

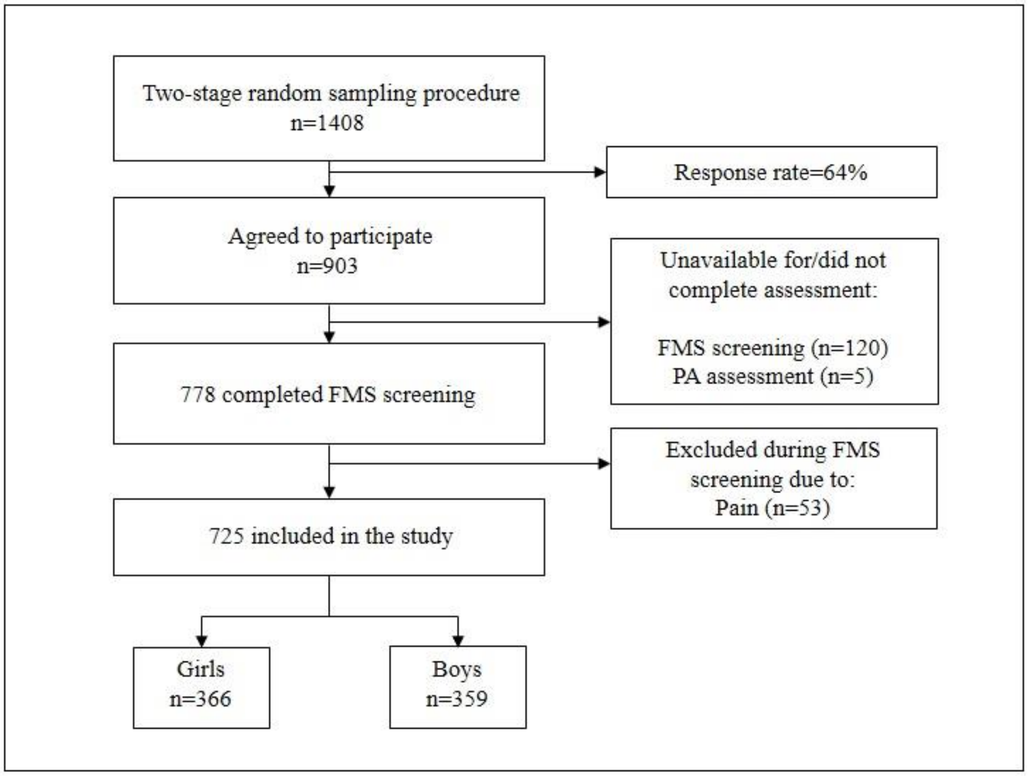

Fig. 1. Flowchart of included participants.

2.2. Procedures

2.2.1. Outcome: total Functional Movement Screen score

The most widely used screening tool for the assessment of movement quality is the FMS™ (Cook et al., 2006a; Cook et al., 2006b). The FMS™ consists of seven basic movement patterns: the deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability. Ten novice trained raters performed FMS™ assessment using a standardized procedure according to literature (Cook et al., 2006a; Cook et al., 2006b). Evidence demonstrates that 2-h education on using FMS™ as a screening tool is needed to reach acceptable interrater and intrarater reliability (Smith, Chimera, Wright, & Warren, 2013). However, our raters underwent two-day education and training procedures by FMS™ certified practitioner.

Moreover, two familiarization sessions were conducted to optimize the consistency and accuracy of raters. Each participant had a maximum of 3 trials for each test following the recommended protocol (Cook et al., 2006a; Cook et al., 2006b). Each test was scored on a three-point scale, from 0 to 3, with higher scores indicating better functional movement. It has been shown that pain can alter movement control (Sterling, Jull & Wrigh, 2001). Therefore, participants were asked if they felt pain during the FMS™ testing procedure, and were subsequently excluded if answered positively to the question (n = 53). For each test, the highest score from the three trials was recorded. An overall composite score was calculated by summing the seven individual tests with a total FMS score of 21 according to standardized guidelines (Cook et al., 2006a; Cook et al., 2006b).

2.2.2. Main predictors: Physical activity level variables

In order to assess PA, the School Health Action, Planning, and Evaluation System (SHAPES) questionnaire was used to assess PA via a computerized version (Wong, Leatherdale, & Manske, 2006). This questionnaire is constituted of 45 multiple-choice questions and was specifically designed for repeated school-based surveys. Two items request a 7-d recall of vigorous PA (VPA) and moderate PA (MPA), respectively. Responses are provided by indicating the number of hours and 15-min increments that each type of PA was performed for each day of the previous week. Therefore, the intensity, duration, and frequency of PA were documented, and the total volume of PA calculated. The average time during the day spent while performing moderate-to-vigorous PA (MVPA) was calculated by summing the weekly time spent performing VPA and MPA divided by 7. Wong et al. (Wong et al., 2006) reported that MVPA estimated using the SHAPES questionnaire correlated moderately with the values of the accelerometer device (r = 0.44). The results of this PA questionnaire can be comparable with other instruments for adolescents as prior reliability research using the SHAPES questionnaire showed moderate agreement for moderate and vigorous PA (Wong et al., 2006).

2.2.3. Secondary predictors: variables of different type of physical activity

The original SHAPES questionnaire was supplemented with two YES/NO questions inquiring about regular participation in organized sports in school, as well as outside of the school. For participants who stated that they participate in organized sport, a comprehensive list of sports activities was offered, and participants identified all the sports in which they regularly participated. In this study, participation in different sports activities indicated the type of PA.

2.2.4. Confounders: Body fat, socioeconomic status and age

Skinfold measurements were taken on the right side of the body at the following sites to the nearest 0.2 mm using Harpenden skinfold calliper (British indicators, West Sussex, UK): 1) triceps fold - at the back of the upper arm, halfway between the acromion process and the olecranon process, 2) subscapular diagonal fold about 2 cm below the lower angle of the scapula. Body fat percentage was calculated using the Slaughter's equation (Slaughter et al., 1988). All measurements were taken by an experienced technician in triplicate and median values were retained for the analyses.

Socioeconomic status (SES) of adolescents was assessed by using a subjective rating of their perceived socio-economical position within the population. Perceived SES was assessed through a one item question: "How would you rate your socioeconomic status? ". Responses were as follows: 1- Much lower than average, 2- Lower than average, 3- Average, 4- Higher than average, 5- Much higher than average. Additionally, chronological age was expressed in years and was added in all multilevel model analysis as a confounder.

2.3. Data analysis

A multilevel modelling approach was used to examine the effect of different levels of PA on the total FMS score. In this research, we primarily relied on the approach developed by the Centre for Multilevel Modelling - University of Bristol (Rasbash, Steele, Browne, & Goldstein, 2019). Multilevel modelling is an elongation of standard multiple regression, where the data have a hierarchical or clustered structure (Rasbash et al., 2019). The process of multilevel modelling was divided into three steps. In the beginning, for each predictor, we built the first model (e.g. level-one model). After that, the second model was built (e.g. level-two model) (in this way, the first step of multilevel modelling was completed). Next, these two models were compared with the likelihood ratio test (LR test) and tested for significance (the second step was completed). Thirdly, the model with a better fit was chosen (end of the third step). After the aforementioned three-step process was done, the next model (e.g. three-level model) was introduced and this process was repeated (from first to the third step). To obtain the final model, this process was iterative, resulting in the number of different models in which the model with the best fit was eventually chosen (final model) (Rasbash et al., 2019). Only the results of the final models for each predictor are presented in this paper. The simplified workflow of the three-step multilevel approach used in this study is shown in Fig. 2. Detailed procedures on the model building are described in the results section.

According to prior evidence from the literature, sex has a significant influence on PA level (Telford, Telford, Olive, Cochrane, & Davey, 2016) and total FMS score (Abraham et al., 2015) during adolescence. Therefore, the sample was stratified by sex, and all further multilevel analyses were performed separately for boys and girls. We performed two waves of analysis: 1) *a priori* and 2) *a posteriori analysis*.

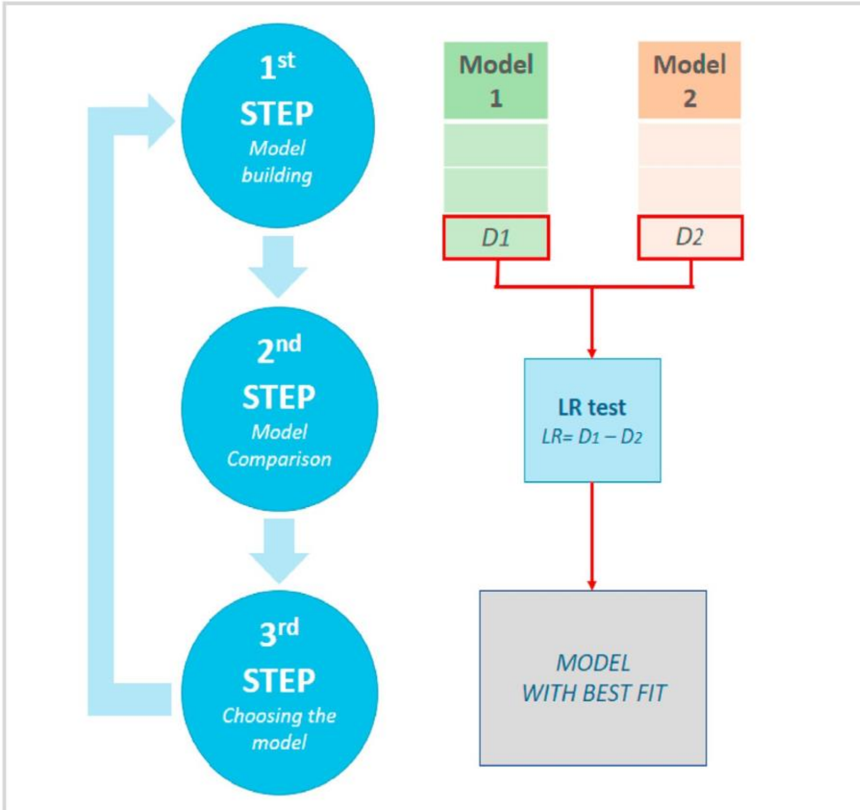

Fig. 2. The simplified three-step multilevel approach.

2.3.1. A priori analysis

To examine the effect of different levels of PA on functional movement, the outcome was the total FMS score with the following predictors: MPA, MVPA, and VPA. Each of the predictors was examined in a separate analysis. This approach resulted in six separate analyses (three for girls and three for boys). Based on evidence from the literature, age (Lester et al., 2017) and body composition (Duncan et al., 2013; Duncan & Stanley, 2012; Molina-Garcia et al., 2019) have a significant influence on the FMS score. Also, SES was added as a confounder. Therefore, for each analysis, the confounders of age, body fat, and SES were introduced in all models.

2.3.2. A posteriori analysis

In the second wave, we took the explorative approach to examine which type of PA contributed most to this kind of results. Therefore, in addition to prior analysis, we included sport participation as an additional predictor. In this way, participation in various sports activities (e.g. football, basketball, etc.) was included as a secondary predictor. To investigate which sports activities are most common among boys and girls, frequency tables of participation in various sports were made. Sports activities in which the prevalence was above 15% were considered for further analysis. This approach also resulted in six separate analyses (three for girls and three for boys). In this study, descriptive data are presented as mean values ± SD. Estimates (coefficient) are presented as unstandardized and noted with the beta symbol (β). Multilevel analysis was performed by using statistical package MLwiN (version 3.04) (Charlton, Rasbash, Browne, Healy, & Cameron, 2019) while for descriptive analysis statistical package Statistica (version 13.5) was used. The level of the statistical significance was set at $p < 0.05$.

3. Results

Table 1 presents the basic characteristics of participants, stratified by sex. Among girls who participated in sports, the most common sports activities included dance and volleyball, while football, basketball, and combat sports were the most common sports activities among active boys. In this study, data have a three-level hierarchical structure where students are at level-1, nested within classes at level-2, nested within schools at level-3. However, after calculating variation partition coefficient (VPC) and introducing variance component models at level-one, level-two and level-three, the data showed significant clustering only at level-two. This can also be seen after plotting the total FMS score by schools (see Fig. 3).

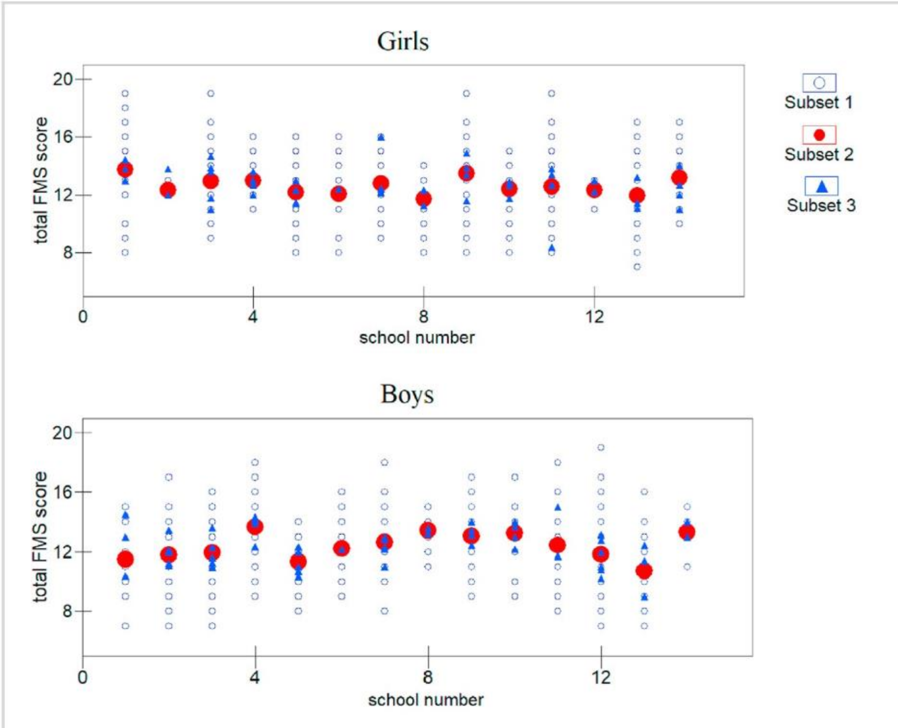

Fig.3. Scatterplot of total FMS score by school number for boys and girls separately. Subset 1 - students, Subset 2 - classes, Subset 3 - schools.

To obtain information about how much clustering there was in the data, VPC was calculated and showed substantial clustering at level-two. More specifically, VPC at level-two indicated that 12.89% and 13.38% of total FMS score variation lies within classes (level two), and 87.10% and 86.61% of variation lies between girls and boys, respectively (among girls: VPC=0.1289; among boys: VPC=0.1338). Expressed as an intraclass correlation coefficient (ICC), where VPC¼ICC, the correlation in total FMS score within classes is 0.128 for girls, and 0133 for boys. Therefore, clustering at level-two or non-independence exists in our data. When the level three model was introduced, level-three deviance (D3) did not drop compared to level-two deviance (D2) (among girls: D3=1644.926; among boys: D3=1654.066). On the other hand, D2 dropped by 15.15 and 17.66 points compared to level-one deviance (D1) among girls and boys respectively (among girls: LR=D1-D2=1669.031-1653.881=15.15; among boys: LR=D1-D2=1662.58-

1644.93=17.66). In addition, quantile-quantile plots (Q-Q plots) were performed to assess assumptions made about residuals for the class (level-two) and students (level one) level according to the literature (Rasbash et al., 2019). The plots showed an approximately straight line, suggesting that the normality assumption at level-two is reasonable (see Supplement files FigS1 and FigS2). Therefore, all further models were built at level-two.

Table 1. Basic characteristics of participants stratified by sex.

	Age (yrs) mean (SD)	Total FMS score mean (SD)	% Body Fat mean (SD)	MVPA (min/day) median (IQR)	MPA (min/day) median (IQR)	VPA (min/day) median (IQR)	Sport part n (%)	School type n (%)		SES median (IQR)
								Voc	Gra	
Boys	16.70 (0.4)	12.23 (2.45)	207 (6.9)	120 (84)	49 (36)	62 (47)	173 (48)	242 (67)	117 (33)	3 (1)
Girls	16.6 (0.4)	12.73 (2.4)	21.5 (5.5)	85 (109)	41 (60)	39 (62)	93 (25)	185 (51)	181 (50)	3 (1)

Total FMS score: total Functional Movement Screen score; % Body Fat: Percentage of Body Fat; MPA: Moderate Physical Activity; MVPA: Moderate-to-Vigorous Physical Activity; VPA: Vigorous Physical Activity; Sport part n(%): Number and percentage (%) of participant that participated in sport; School type n (%): number of participant in each type of school; Voc: Vocational school; Gra: Grammar school; SES: socioeconomic status (1- Much lower than average, 2- Lower than average, 3- Average, 4- Higher than average, 5- Much higher than average); IQR: interquartile range; ±SD: ± Standard Deviation.

Following this, the three-step multilevel approach was carried on. First, the random-intercept model was built and included one of the predictors (e.g. VPA) and all confounders (age, SES, and body fat percentage). After that, a random-slope model for one of the predictors (e.g. VPA) was built. Next, these models were compared with a likelihood ratio test (LR test). LR test was performed to choose the model with a better fit according to the literature (Rasbash et al., 2019). After that, the model with a better fit was chosen. Finally, in all analyses, all coefficients of predictor variables were modelled as random at level-two. This approach resulted in six separate analysis and the results are presented in the paragraphs below (Tables 2 and 3). The coefficients in the tables are mean unstandardized coefficients representing relationships between total FMS score and the various dependent measures (predictors). Within the all analyses, the addition of confounders did not result in the improvement of the fit statistic as well as in the statistical significance of the associated coefficient. Because nonsignificant confounders can influence the predictor coefficient they were retained in the models (Skelly, Dettori, & Brodt, 2012). Data from 83 participants were missing for body fat. Since the MLwiN package can handle missing data, all analyses were carried out regularly and included body fat as a confounder. Also, age was centered around the value of 17 (coded as Age-17).

3.1. Results of a priori analysis

3.1.1. Effect of different levels of PA on total FMS score in girls

In the evaluation of the effects of MVPA, MPA, and VPA level on total FMS score, models with the best fit in girls resulted in random intercept models at level-two. When the model was adjusted for age, SES, and body fat percentage, MVPA, and VPA showed minor but significant effects on total FMS score ($\beta=0.005$, $p=0.006$; $\beta=0.011$, $p=0.001$, respectively). However, slope coefficients for MPA failed to reach statistical significance ($\beta=0.004$, $p=0.157$) (see Table 2). For example, in the above analysis of the relationship between total FMS score and VPA in girls, the slope coefficient for VPA was estimated to be 0.011 and it is shared by all classes (see Table 2 for the results). This means that a 100-min increase in daily VPA, therefore, corresponds to a 1.1 points increase in total FMS score, holding other confounders constant. When evaluating these coefficients, it is important to consider that each of the coefficients represents a relationship that was adjusted for the other confounders because age, SES, and body fat percentage were included in every analysis.

Table 2. Level-two random-intercept models for predictors: MPA, MVPA, and VPA for girls.

response	**total FMS score**								
predictor	**MVPA**			**MPA**			**VPA**		
parameter	**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**
Fixed Part									
cons	12.141	0.747	0.000	12.620	0.729	0.000	12.115	0.732	0.000
MVPA	**0.005**	**0.002**	**0.006**	-	-	-	-	-	-
MPA	-	-	-	**0.004**	**0.003**	**0.157**	-	-	-
VPA	-	-	-	-	-	-	**0.011**	**0.003**	**0.001**
%BF	0.017	0.023	0.480	0.017	0.024	0.472	0.015	0.023	0.518
(Age-17)	0.296	0.365	0.417	0.355	0.368	0.336	0.326	0.362	0.368
SES	-0.055	0.164	0.739	-0.103	0.164	0.529	-0.027	0.164	0.870
Random Part									
Level 2 variance	0.727	0.317		0.754	0.328		0.744	0.321	
Level 1 variance	4.760	0.412		4.839	0.418		4.704	0.406	

Functional Movement Screen; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; MPA: Moderate Physical Activity; MVPA: Moderate-to-Vigorous Physical Activity; VPA: Vigorous Physical Activity; SES: socioeconomic status; estimate (β): unstandardized beta coefficient; S.E.: Standard Error; p: p-value.

3.1.2. Effect of different levels of PA on total FMS score in boys

In boys, the evaluation of the effects of MVPA, MPA, and VPA level on total FMS score, resulted in random-intercept models at level-two as the models with the best fit. When the model was adjusted for age, SES, and body fat percentage, MVPA and MPA slope coefficients failed to show statistical significance (β=0.000, p=0.78; β= -0.002, p=0.455).

Table 3. Level-two random-intercept models for predictors: MPA, MVPA, and VPA for boys.

response	**total FMS score**								
predictor	**MVPA**			**MPA**			**VPA**		
parameter	**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**
Fixed Part									
cons	12.194	0.657	0.000	12.402	0.629	0.000	11.918	0.651	0.000
MVPA	**0.000**	**0.001**	**0.780**	-	-	-	-	-	-
MPA	-	-	-	**-0.002**	**0.002**	**0.455**	**-**	**-**	**-**
VPA	-	-	-	-	-	-	**0.004**	**0.003**	**0.158**
%BF	0.008	0.019	0.693	0.008	0.019	0.667	0.006	0.019	0.748
SES	-0.050	0.164	0.761	-0.070	0.162	0.666	-0.006	0.165	0.972
(Age-17)	0.042	0.352	0.906	0.039	0.351	0.911	0.098	0.353	0.782
Random Part									
Level 2 variance	0.659	0.313		0.648	0.310		0.679	0.317	
Level 1 variance	5.476	0.457		5.473	0.457		5.431	0.453	

intercept; total FMS score: Functional Movement Screen; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; MPA: Moderate Physical Activity; MVPA: Moderate-to-Vigorous Physical Activity; Vigorous Physical Activity; SES: socioeconomic status; estimate (β): unstandardized beta coefficient; S.E.: Standard Error; p: p-value.

However, the VPA slope resulted in a more relevant but not statistically significant coefficient (β=0.004, =0.158) (see Table 3). MVPA, MPA, and VPA were not significant predictors of total FMS score in boys as was seen in girls, even after adjusting for relevant confounders from the literature. To examine why these discrepancies in results exist, *a posteriori* explorative analysis were carried that included PA type as an additional explanatory variable.

3.2. Results of a posteriori analysis

To investigate the potential influence of the type of PA on total FMS score, *a posteriori* explorative analysis were carried on with sport participation as an additional explanatory variable (secondary predictor). In these analyses, sport participation denotes the type of PA. Among girls who participated in sports, the most common sports activities included dance (30%) and volleyball (25%). However, football (36%), basketball (18%) and combat sports (15%) were the most common sports activities among active boys. Therefore, in the second wave of analysis, all previous models included additional predictors - football, basketball and combat sports (for boys), and volleyball and dance (for girls).

This was done by adding and excluding each predictor one by one in all analyses. If a student did not participate in a particular sport, it was coded as 0 (zero), while the value of 1 was coded if that participant participated in a specific sport. After including the type of PA in the models for girls, the coefficient for the main predictors (e.g. MPA) did not change and remained insignificant (see Appendix 1). However, different types of PA were related to higher total FMS score in girls (when MPA was main predictor, β for dance was 0.972 with a p-value of 0.043; β for volleyball was 1.003 with a p-value of 0.071) (See Table 4). For detailed results and effects of a particular type of PA and confounders on the total FMS, score see Appendix 1 (Tables A1-A3).

Table 4. Level-two random-intercept models for predictors MVPA, MPA, and VPA in girls, including different types of PA as the secondary predictors.

response		**total FMS score**								
parameter		**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**
main predictors	**MVPA**	0.004	0.002	0.011	-	-	-	-	-	-
	MPA	-	-	-	0.004	0.003	0.125	-	-	-
	VPA	-	-	-	-	-	-	**0.009**	**0.003**	**0.006**
secondary predictors	**Volleyball**	0.875	0.551	0.112	1.003	0.556	0.071	0.653	0.559	0.243
	Dance	0875	0.480	0.068	**0.972**	**0.481**	**0.043**	0.801	0.482	0.096

total FMS score: Total Functional Movement Screen Score**;** estimate (β): unstandardized beta coefficient; S.E.: Standard Error; p: p-value.; MVPA: Moderate-to-Vigorous Physical Activity; MPA: Moderate Physical Activity; VPA: Vigorous Physical Activity.

Interestingly, among boys, significance and slope coefficient for VPA changed after including participation in football (β for VPA changed from 0.004 to 0.005, and p-value changed from 0.173 to 0.089, b for football was 0.569 with a p-value of 0.118) (see Table 5 and Appendix 1 for detailed results). After the inclusion of the type of PA (basketball and combat sports), none of the additional predictors reached statistical significance while investigating relations between

MVPA, MPA, or VPA and total FMS score (see Table 5). For detailed results see Tables A4-A6 in Appendix 1). Although this change did not reach statistical relevance according to the classic statistical approach, these results are showing a positive trend considering the relationships between VPA and FMS score among boys, after the inclusion of the type of PA. This means that type of PA may have an effect on the total FMS score both in girls and boys.

Table 5. *Level-two random-intercept models for predictors MVPA, MPA, and VPA in boys, including different types of PA as the secondary predictors.*

response		**total FMS score**								
parameter		**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**	**estimate (β)**	**S.E.**	**p**
main predictors	**MVPA**	-0.002	0.002	0.475	-	-	-	-	-	-
	MPA	-	-	-	-0.002	0.002	0.475	-	-	-
	VPA	-	-	-	-	-	-	**0.005**	**0.003**	**0.089**
secondary predictors	**Football**	-0.412	0.345	0.244	-0.412	0.345	0.244	-0.569	0.364	0.118
	Basketball	0.126	0.473	0.790	**0.126**	**0.473**	**0.790**	0.010	0.473	0.983
	Combat sports	0.129	0.521	0.805	0.129	0.521	0.805	0.055	0.520	0.915

total FMS score: Total Functional Movement Screen Score**;** estimate **(**β): unstandardized beta coefficient; S.E.: Standard Error; p: p-value.; MVPA: Moderate-to-Vigorous Physical Activity; MPA: Moderate Physical Activity; VPA: Vigorous Physical Activity.

4. Discussion

This is the first study to examine the relationship between PA and functional movement in the adolescent population. The results presented here are unique and extend scientific understanding of the role that functional movement plays in establishing positive trajectories of PA in youth. Our results demonstrate that MVPA and VPA are significant predictors of total FMS score in adolescent girls (β=0.005, p=0.006 and β=0.011, p=0.001, respectively). Moreover, the results of this study show, for the first time, that the way in which type of PA influences FMS score is different among boys and girls. In girls, participation in dance was a significant predictor of total FMS (β for dance participation 0.97, p=0.043). However, among boys, neither of predictors showed a significant contribution to the total FMS score.

Our results, using a large adolescent sample, are in line with previous studies, performed with children, that showed similar relationships between these variables. To date, two similar studies have investigated the relation between PA and FMS in children and young adolescents (Duncan & Stanley, 2012; Molina-Garcia et al., 2019). Prior work by Duncan and Stanley (Duncan & Stanley, 2012), investigated 10-11-year-old children (n = 58), reported that total FMS score was significantly positively related to PA (r =0.301). In this study BMI and PA were both significant predictors of functional movement, predicting 60.2% of the variance in total FMS score, whereas average steps/day predicted 7.3% of the variance in total FMS score (p=0.0001, Adjusted R2=0.602). Molina-Garcia et al. (2019) found that fitness level was positively related to the total FMS score. The results presented by Molina-Garcia et al. (Molina-Garcia et al., 2019) suggested that children with a higher level of fitness showed better movement quality, independent of their fatness level. Although these prior studies were performed on different populations of children (aged from 8 to 12 and obese children and young adolescents), the results of the current study align with the prior work of Duncan and Stanley (Duncan & Stanley, 2012) and Molina-Garcia et al. (Molina-Garcia et al., 2019). Although our research confirms some previous findings, a potential explanation in the mentioned studies is still lacking (Duncan & Stanley, 2012; Molina-Garcia et al., 2019). The questions that remain open are: 1) Why is this relationship positive? and 2) What are the mechanisms behind this relationship? Although this cross-sectional study revealed a weak relationship between PA levels and functional movement, we suggest two main potentially overlapping relationships behind this phenomena: *1)*

Neuromuscular relationship: A higher PA level is usually related to better motor coordination and motor proficiency (Wrotniak, Epstein, Dorn, Jones, & Kondilis, 2006), and postural control (Baghbani, Woodhouse, & Gaeini, 2016), which can, in turn, be related to a better quality of movement patterns. At the same time, evidence suggests that a lower level of PA is related to suboptimal proprioception (Ribeiro & Oliveir, 2011) and may limit motor control leading to dysfunctional movement patterns; *2) Psychomotor relationship*: Children who are more engaged in PA and sports activities have a wider variety of movement patterns. Through sports activities and practices, children are engaged in the motor learning process where they learning different movement patterns. It has been shown how multiple motor learning experiences can enhance motor adaptability (Seidler, 2004). This could have a positive effect on movement quality. However, our findings suggest that the psychomotor and neuromuscular relationship between movement patterns and type of PA can be specific. According to the results of our study, it seems that engaging in different types of sports activities has a different effect on movement quality.

More specifically, our results indicate that there might be a positive relationship between volleyball and the movement quality in girls. This may be because volleyball players are more familiar with FMS patterns as similar movement patterns are more common in this sport (squat, shoulder flexion, in-line lunge). In addition, female volleyball players have greater flexibility than other athletes (Dopsaj,1994). Our results show that this is also true for dancers, as female dancers show better postural control, balance, proprioception, motor control (Kilroy, Crabtree, Crosby, Parker, & Barfield, 2016), and better joint mobility during the adolescent period (Steinberg et al., 2006). These factors can have a positive effect on movement quality. However, based on another screening tool, Lee et al. reported that pre-professional dancers also have high levels of injury and suboptimal movement quality during the adolescent period (Lee, Reid, Cadwell & Palmer, 2017). Conversely, the results of this study indicate that participation in football is negatively related to movement quality among boys. Although this relationship did not reach statistical significance, it is important to note that previous studies have shown that football players are exhibiting progressive limitation in flexibility and joint mobility through adolescence (Cejudo et al., 2019) and have a greater risk for degenerative hip joint problems already at the early age of adolescence (de Silva, Swain, Broderick, & McKay, 2016). Therefore, future studies should specifically address the differential influence of various PA on movement quality of children and adolescents. As opposed to football, participation in basketball was not significantly related to functional movement in boys. There is obvious sex difference in relation between different types of PA and functional movement. In this study, girls are in the last stage of maturation, while boys are not which could potentially influence quality of movement in both sexes. This can also explain the difference between boys and girls related to the association between type of PA and functional movement. However, more studies are needed in order to examine effect of maturation on functional movement and different types of PA in the adolescent population.

The results of the present study underline the importance of developing functional movement during childhood and adolescence. Providing children and youth with the opportunity to develop functional movement should be considered a key antecedent in enabling children to lead physically active lives. In other words, intensive PA does not guarantee optimal movement quality since engaging in some type of sport activities, especially when exercise intensity is higher than a person's physical fitness level, can result in dysfunctional movement patterns. Conclusively, from a practical point of view, our findings could be incorporated into practice as follows: 1) functional movement patterns should be practiced in isolated manner, independently of practicing specific sport and other physical activities. In line with this, integration of different injury prevention programs, especially those which facilitate functional movement, such as of '11 + Kids' may be beneficial (Beaudouin et al., 2019). 2) Learning a variety of movement patterns, as well as practicing learned movements and activities at moderate-to-vigorous intensity could be beneficial to potentially reduce the risk of injury incidence, potential orthopaedic abnormalities, and cardiovascular diseases in later life.

4.1. Strengths and limitations

Several strengths of this study should be highlighted. To the authors knowledge, this is the first study adequately powered study that has investigated the relationship between functional movement quality and PA level in adolescents. Second, this is the only study that has applied multilevel methodology to predict functional movement via various PA parameters in the pediatric population. This results in less biased results (e.g. ecological fallacy is reduced) and clearer conclusions can be drawn. Finally, this study controls for a multitude of different variables that should allow a more accurate prediction of functional movement in the adolescent population (sex, age, percentage of body fat, and socioeconomic status). However, there are also some limitations that need to be acknowledged. This study has a cross-sectional design that limits causal interpretations. In this research, 10 raters were recruited. However, all raters underwent the same education and FMS testing protocol. In addition, previous studies consistently showed good interrater agreement in FMS scores (Smith et al., 2013; Teyhen et al., 2012). Also, this research included mostly urban adolescent population, while excluding adolescents from rural areas. This can potentially limit the generalizability of the results.

Collectively, the results of the present study provide valuable information for those working in physical education, youth sport, and public health, on the contribution of different levels of PA on functional movement quality of the adolescent population. Further research should focus on the examination of different predictors affecting the movement quality in different populations. Since the application of a multilevel methodology is lacking in this research area, we strongly encourage the application of the multilevel methodology for future researchers when appropriate. This approach will yield a more accurate prediction that in turn could be better translated into practice.

5. Conclusion

To this date, there are no studies that have investigated the relationship between various parameters of PA and functional movement in the mid adolescent population. Our study demonstrates that the level of PA is positively associated with functional movement in adolescent girls, but not in boys, where the type of PA moderates these associations. Developing functional movement during childhood and adolescence should therefore be considered essential for optimal musculoskeletal health. Therefore, undertaking functional movement patterns should be practiced in isolated manner as well as practicing learned functional movement patterns and activities at moderate-to-vigorous intensity could be beneficial to potentially reduce future risk of injury incidence, orthopaedic abnormalities, and cardiovascular diseases in later life.

Ethical approval

The Ethics Committee of the Faculty of Kinesiology at the University of Zagreb (Croatia) approved the procedures of this study (No: 1009-2014) which was executed according to the Declaration of Helsinki. The written consent of the parents or legal guardians of the children was ensured once they have been informed of the study aims, the protocol, and the possible discomforts they might encounter.

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Declaration of competing interest

None declared.

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References

Abraham, A., Sannasi, R., & Nair, R. (2015). Normative values for the functional movement screentm in adolescent school aged children. *International Journal of Sports Physical Therapy*, *10*(1), 29-36.

Baghbani, F., Woodhouse, L. J., & Gaeini, A. A. (2016). Dynamic postural control in female athletes and nonathletes after a whole-body fatigue protocol. *The Journal of Strength & Conditioning Research*, *30*(7), 1942-1947.

Bardenett, S. M., Micca, J. J., DeNoyelles, J. T., Miller, S. D., Jenk, D. T., & Brooks, G. S. (2015). Functional movement screen normative values and validity in high school athletes: Can the Fms^{TM} Be used as a predictor of injury? *International Journal of Sports Physical Therapy*, *10*(3), 303-308.

Beaudouin, F., Ro€ssler, R., Aus Der Fünten, K., Bizzini, M., Chomiak, J., Verhagen, E., et al. (2019). Effects of the “11+ Kids” injury prevention programme on severe injuries in children’s football: A secondary analysis of data from a multicentre cluster-randomised controlled trial. *British Journal of Sports Medicine*, *53*(22), 1418-1423.

Bonazza, N. A., Smuin, D., Onks, C. A., Silvis, M. L., & Dhawan, A. (2017). Reliability, validity, and injury predictive value of the functional movement screen. *American Journal of Sports Medicine*, *45*(3), 725-732.

Browne, W. J., Golalizadeh Lahi, M., & Parker, R. M. A. (2009). *A Guide to sample size Calculations for random effect Models via Simulation and the MLPowSim software school of clinical veterinary sciences*. University of Bristol. http://www.bristol.ac. uk/cmm/.

Campbell, E. L., Seynnes, O. R., Bottinelli, R., McPhee, J. S., Atherton, P. J., Jones, D. A., et al. (2013). Skeletal muscle adaptations to physical inactivity and subsequent retraining in young men. *Biogerontology*, *14*(3), 247-259.

Cejudo, A., Robles-Palazon, F. J., Ayala, F., De Ste Croix, M., Ortega-Toro, E., Santonja-Medina, F., et al. (2019). Age-related differences in flexibility in soccer players 819 years old. *PeerJ*, *7*, Article e6236.

Charlton, C., Rasbash, J., Browne, W. J., Healy, M., & Cameron, B. (2019). *MLwiN*. Centre for Multilevel Modelling, University of Bristol [Computer software] Version 3.04. http://www.bristol.ac.uk/cmm/.

Cook, G. (2011). *Movement: Functional movement systems: Screening, assessment and corrective strategies* (1st ed.). Aptos: Lotus Pub.

Cook, G., Burton, L., & Hoogenboom, B. (2006a). Pre-participation screening: The use of fundamental movements as an assessment of function - part 1. *North American journal of sports physical therapy: NAJSPT*, *1*(2), 62-72.

Cook, G., Burton, L., & Hoogenboom, B. (2006b). Pre-participation screening: The use of fundamental movements as an assessment of function - part 2. *North American journal of sports physical therapy: NAJSPT*, *1*(3), 132-139.

Department of Health & Human Services. (2018). *2018 physical activity guidelines advisory committee. 2018 physical activity guidelines advisory committee scientific report*. Washington, DC: U.S. Department of Health and Human Services.

Ding, D., Lawson, K. D., Kolbe-Alexander, T. L., Finkelstein, E. A., Katzmarzyk, P. T., van Mechelen, W., et al. (2016). The economic burden of physical inactivity: A global analysis of major non-communicable diseases. *The Lancet*, *388*(10051), 1311-1324.

Dopsaj, M. (1994). Extent of flexibility among athletes in different sports games: Soccer, volleyball, basketball and handball. In *Facta universitatis-series: Physical education* (Vol. 1, pp. 51-60).

Dorrel, B. S., Long, T., Shaffer, S., & Myer, G. D. (2015). Evaluation of the functional movement screen as an injury prediction tool among active adult populations: A systematic review and meta-analysis. *Sport Health*, *7*(6), 532-537.

Dossa, K., Cashman, G., Howitt, S., West, B., & Murray, N. (2014). Can injury in major junior hockey players be predicted by a pre-season functional movement screen - a prospective cohort study. *Journal of the Canadian Chiropractic Association*, *58*(4), 421-427.

Duncan, M. J., & Stanley, M. (2012). Functional movement is negatively associated with weight status and positively associated with physical activity in British primary school children. *Journal of obesity*, 2012, Article 697563.

Duncan, M. J., Stanley, M., & Leddington Wright, S. (2013). The association between functional movement and overweight and obesity in British primary school children. *BMC sports science, medicine & rehabilitation*, *5*, 11.

Frank, C., Kobesova, A., & Kolar, P. (2013). Dynamic neuromuscular stabilization & sports rehabilitation. *International Journal of Sports Physical Therapy*, *8*(1), 62-73.

Garrison, M., Westrick, R., Johnson, M. R., & Benenson, J. (2015). Association between the functional movement screen and injury development in college athletes. *International Journal of Sports Physical Therapy*, *10*(1), 21-28.

Kiesel, K. B., Butler, R. J., & Plisky, P. J. (2014). Prediction of injury by limited and asymmetrical fundamental movement patterns in American football players. *Journal of Sport Rehabilitation*, *23*(2), 88-94.

Kilroy, E. A., Crabtree, O. M., Crosby, B., Parker, A., & Barfield, W. R. (2016). The effect of single-leg stance on dancer and control group static balance. *International journal of exercise science*, *9*(2), 110-120.

Kraus, K., Schütz, E., Taylor, W. R., & Doyscher, R. (2014). Efficacy of the functional movement screen: A review. *Journal of strength and conditioning research*, *28*(12), 3571-3584.

Lee, L., Sp, P., Medicine, E., Msk, P. P., Reid, D., Physio, P. M., et al. (2017). Original research injury incidence, dance exposure and the use of the movement competency screen (MCS) to full-time pre- professional dancers. *The International Journal of Sports Physical Therapy*, *12*(3), 352-370.

Lester, D., McGrane, B., Belton, S., Duncan, M., Chambers, F., & O'Brien, W. (2017). The age-related association of movement in Irish adolescent youth. *Sports*, *5*(4), 77.

Mahdieh, L., Zolaktaf, V., & Karimi, M. T. (2020). Effects of dynamic neuromuscular stabilization (DNS) training on functional movements. *Human Movement Science*, *70*, 102568.

Molina-Garcia, P., H Migueles, J., Cadenas-Sanchez, C., Esteban-Cornejo, I., Mora-Gonzalez, J., Rodriguez-Ayllon, M., et al. (2019). Fatness and fitness in relation to functional movement quality in overweight and obese children. *Journal of Sports Sciences*, *37*(8), 878-885.

Quatman-Yates, C. C., Quatman, C. E., Meszaros, A. J., Paterno, M. V., & Hewett, T. E. (2012). A systematic review of sensorimotor function during adolescence: A developmental stage of increased motor awkwardness? *British Journal of Sports Medicine*, *46*(9), 649-655.

Rasbash, J., Steele, F., Browne, W. J., & Goldstein, H. (2019). *A User's Guide to MLwiN (v3.04.)*. Centre for Multilevel Modelling, University of Bristol. http://www. bristol.ac.uk/cmm/.

Ribeiro, F., & Oliveir, J. (2011). Factors influencing proprioception: What do they reveal? In V. Klika (Ed.), *Biomechanics in application* (pp. 323-346). IntechOpen. https://doi.org/10.5772/20335. https://www.intechopen.com/books/ biomechanics-in-applications/factors-influencing-proprioception-what-dothey-reveal.

Seidler, R. D. (2004). Multiple motor learning experiences enhance motor adaptability. *Journal of Cognitive Neuroscience*, *16*(1), 65-73.

Shojaedin, S. S., Letafatkar, A., Hadadnezhad, M., & Dehkhoda, M. R. (2014). Relationship between functional movement screening score and history of injury and identifying the predictive value of the FMS for injury. *International Journal of* I*njury Control and Safety Promotion*, *21*(4), 355-360.

de Silva, V., Swain, M., Broderick, C., & McKay, D. (2016). Does high level youth sports participation increase the risk of femoroacetabular impingement? A review of the current literature. *Pediatric Rheumatology*, *14*(1), 1-7.

Skelly, A., Dettori, J., & Brodt, E. (2012). Assessing bias: The importance of considering confounding. *Evidence-Based Spine-Care Journal*, *3*, 9-12, 01.

Slaughter, M. H., Lohman, T. G., Boileau, R. A., Horswill, C. A., Stillman, R. J., Van Loan, M. D., et al. (1988). Skinfold equations for estimation of body fatness in children and youth. *Human Biology*, *60*(5), 709-723.

Smith, C. A., Chimera, N. J., Wright, N. J., & Warren, M. (2013). Interrater and intrarater reliability of the functional movement screen. *Journal of strength and conditioning research*, *27*(4), 982-987.

Štefan, L., Sorić, M., Devrnja, A., Podnar, H., & Mišigoj-Duraković, M. (2017). Is school type Associated with objectively measured physical activity in 15-year-olds? *International Journal of Environmental Research and Public Health*, *14*(11).

Steinberg, N., Hershkovitz, I., Peleg, S., Dar, G., Masharawi, Y., Heim, M., et al. (2006). Range of joint movement in female dancers and nondancers aged 8 to 16 years: Anatomical and clinical implications. *American Journal of Sports Medicine*, *34*(5), 814-823.

Sterling, M., Jull, G., & Wright, A. (2001). The effect of musculoskeletal pain on motor activity and control. *Journal of Pain*, *2*(3), 135-145.

Telford, R. M., Telford, R. D., Olive, L. S., Cochrane, T., & Davey, R. (2016). Why are girls less physically active than boys? Findings from the LOOK longitudinal study. *PloS One*, *11*(3), 1-11.

Teyhen, D. S., Shaffer, S. W., Lorenson, C. L., Halfpap, J. P., Donofry, D. F., Walker, M. J., et al. (2012). The functional movement screen: A reliability study. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(6), 530-540.

Wong, S. L., Leatherdale, S. T., & Manske, S. (2006). Reliability and validity of a school-based physical activity questionnaire. *Medicine & Science in Sports & Exercise*, *38*(9), 1593-1600.

Wrotniak, B. H., Epstein, L. H., Dorn, J. M., Jones, K. E., & Kondilis, V. A. (2006). The relationship between motor proficiency and physical activity in children. *Pediatrics*, *118*(6).

Study 2: Is Adiposity Associated with the Quality of Movement Patterns in the Mid-Adolescent Period?

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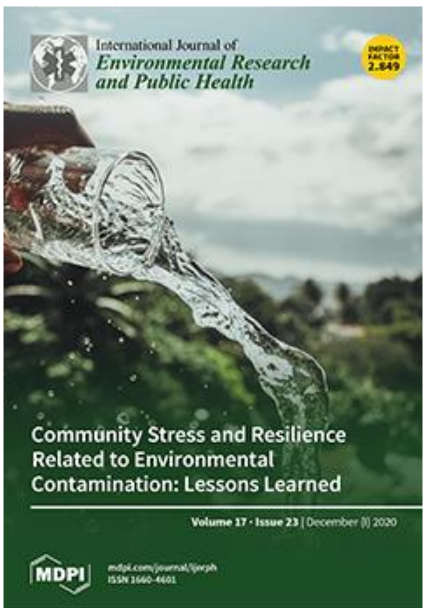

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Is Adiposity Associated with the Quality of Movement Patterns in the Mid-Adolescent Period?

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Abstract: This study examined the association between functional movement (FM) and adiposity in adolescent population (16–17 years). This study was conducted in a representative sample of urban adolescents as the part of the CRO-PALS longitudinal study (n = 652). Body mass index (BMI), a sum of four skinfolds (S4S), waist and hip circumference were measured, and FM was assessed via Functional Movement Screen™ (FMS™). Furthermore, total FMSTM screen was indicator of FM with the composite score ranged from 7 to 21, with higher score indicating better FM. Multilevel analysis was employed to determine the relationship between different predictors and total FMS score. In boys, after controlling for age, moderate-to-vigorous physical activity, and socioeconomic status, total FMS score was inversely associated with BMI (β= -0.18, $p < 0.0001$), S4S (β = -0.04, $p < 0.0001$), waist circumference (β= -0.08, $p < 0.0001$), and hip circumference (β= -0.09, $p < 0.0001$). However, among girls, in adjusted models, total FMS score was inversely associated only with S4S (β= -0.03, $p < 0.0001$), while BMI (β= -0.05, $p = 0.23$), waist circumference (β = -0.04, $p = 0.06$), and hip circumference (β= -0.01, $p = 0.70$) failed to reach statistical significance. Results showed that the association between adiposity and FM in adolescence is sex-specific, suggesting that boys with overweight and obesity could be more prone to develop dysfunctional movement patterns. Therefore, exercise interventions directed toward correcting dysfunctional movement patterns should be sex-specific, targeting more boys with overweight and obesity rather than adolescent girls with excess weight.

Keywords: obesity; paediatric exercise; motor control; motor coordination; motor competence; movement competence

1. Introduction

Childhood obesity presents one of the largest public health problems with serious long-term health consequences. Children with obesity have a higher risk of developing diabetes type 2, cardiovascular diseases, cancer, and musculoskeletal disorders later in life (1–3). Amongst the above-mentioned risks of paediatric obesity, musculoskeletal disorders with associated biomechanical and health impact have been least studied systematically. According to the most recent umbrella review which investigated the association between adiposity and physical function in children with obesity, few published systematic reviews drew attention to the phenomena of the biomechanics of childhood obesity (4). Indeed, only one review pointed to the negative influence of excess weight on movement biomechanics among children with possible long-term consequences on musculoskeletal health (5). This is surprising since musculoskeletal disorders are currently among the most common diseases and one of the leading world health-care problems (6). For example, direct costs of the musculoskeletal diseases among children in the United States amount to more than 7.6 billion USD per year (7). In addition to this, it is well known that pathobiomechanical behaviour is a key factor for the development of postural and musculoskeletal pathologies in children and adults (8–11). However, it remains unknown what role adolescent obesity plays in the development of different pathobiomechanical movement behaviour.

According to the recent evidence, three inter-related clinical and biomechanical components are compromised in children with overweight: (1) body posture (12–16), (2) gait biomechanics (5,17), and (3) movement competence (4,18–20). Compared to normal-weight peers, children with overweight demonstrate postural malalignments characterized by thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum, and varus, valgus heel, and flat feet (12–16). Furthermore, children with overweight have altered biomechanics of gait associated with higher hip and tibiofemoral contact force, and lower limb valgus position (5). Additionally, during walking, these children exhibit increased maximum force beneath the lateral and medial forefoot, greater pressure-time integral beneath the midfoot, and 2nd–5th metatarsal area (17). Along with the postural abnormalities and altered biomechanics of walking, children with overweight have compromised movement competency (18–20). Movement competency is defined as the global movement patterns (i.e., locomotion, object control skills, or stability tasks) essential for the child motor development (21,22). An important aspect of the movement competency, and thus of motor development, is the qualitative component of the movement, often termed as the movement quality.

Functional movement (FM) represents a clinical measure of movement quality (23–25), most commonly assessed via Functional Movement Screen^{TM} (FMS^{TM}) (26,27). FM implies an optimal range of motion, balance, and postural control of the specific movement (26–28). Contrary, dysfunctional movement (DFM) presents suboptimal movement quality and is related to a compensatory movement pattern along the kinetic chain with associated loss in the range of motion, balance, and deficit in postural control of the specific movement pattern (26–28). The importance of FM patterns has been discussed in previous studies (23–27) and they are considered as fundamental 'pillars' for the exhibition of complex movements (26,27), whereas DFM has been related to higher injury incidence (29–32) and potential movement pathologies in children with overweight (19,20,33). Therefore, incorporating FM patterns in exercise programs is critical for the optimal progress toward more complex movement skills (26–28). In addition to the aforementioned consequences of obesity on biomechanics, evidence shows that higher body weight changes motor performance, range of motion (34), balance (34) and leads to poor postural control in children (35), which could potentially endanger the performance of both FM and complex movement skills. Evidence suggest that obesity has a high impact on joint structures responsible for joint stabilization and proprioception (36). Furthermore, obesity leads to degenerative deformities such as osteoarthritis even among children (37). Taking everything into account, postural alteration, coordination deficits, and overweight in childhood could lead to the development of DFM and orthopaedic deformities in the future (1,19,20). This could be concerning since the number of children with overweight and obesity is still increasing around the globe (38). Still, among all previously considered biomechanical components, FM and its relation to the adiposity has not been studied widely.

The development of DFM patterns along with higher body weight through the adolescent period could result in much higher dysfunction on the musculoskeletal system. Moreover, neuromuscular control and movement coordination are not completely developed by the time of adolescence (39). Therefore, investigating relations between adiposity and FM is important for the musculoskeletal health of the mid-adolescents (14–17 yo) as well. Few studies investigated quality of movement and obesity among the paediatric participants with the majority reporting an inverse relationship between FM and weight status (19,20,34,40,41), while only one study revealed no correlation between these two variables (42). However, these studies had a small sample size, or recruited merely participants with overweight/obesity, and did not include mid-adolescents. This makes it difficult to ascertain how FM and adiposity might be related during this period, and without this, scientists, physical educationalists, and clinicians may make erroneous decisions by applying outcomes found on children onto mid-adolescents. To the best of our knowledge, there are no studies that examined the association between FM and adiposity in a large, random sample of mid-adolescents. Therefore, this study aims to bridge this gap by examining the sex differences in FM between mid-adolescents with normal weight and mid-adolescents with overweight and obesity. In addition, this study will thrive to reveal the relationship between variables of adiposity and FM in a representative sample of urban mid-adolescents.

2. Materials and Methods

2.1. Participants

Current study was performed as a part of the 4-year longitudinal study (CRO-PALS) conducted in representative sample of urban youth (city of Zagreb, Croatia). Information about the procedures of the CRO-PALS longitudinal study have been documented in previous research (43). Shortly, using stratified two-stage random sampling procedures (school level and class level), 54 classes in 14 secondary schools were selected to participate in the CRO-PALS study. All 1408 schoolchildren in the selected classes were approached, and 903 agreed to participate (response rate = 64%). 157 participants were not available on the day of assessment or did not perform the FMS^{TM} procedure and anthropometric measurement. As a result, information of 746 mid-adolescents were collected.

To be included in the analyses, all subjects had to meet specific criteria, namely: (1) not reporting any pain while performing FMS^{TM} assessment, and (2) not being classified as a child with underweight according to International Obesity Task Force criteria (44). Accordingly, 94 subjects were excluded. At the end, data on 652 participants were analyzed (girls, n = 321, mean age ± SD = 16.6 ± 0.4 yo; boys, n = 331, mean age ± SD = 16.7 ± 0.4 yo). Measurements were taken in 2015, during March, April, and May. Figure 1 represents a flowchart of the participants that were included in the study.

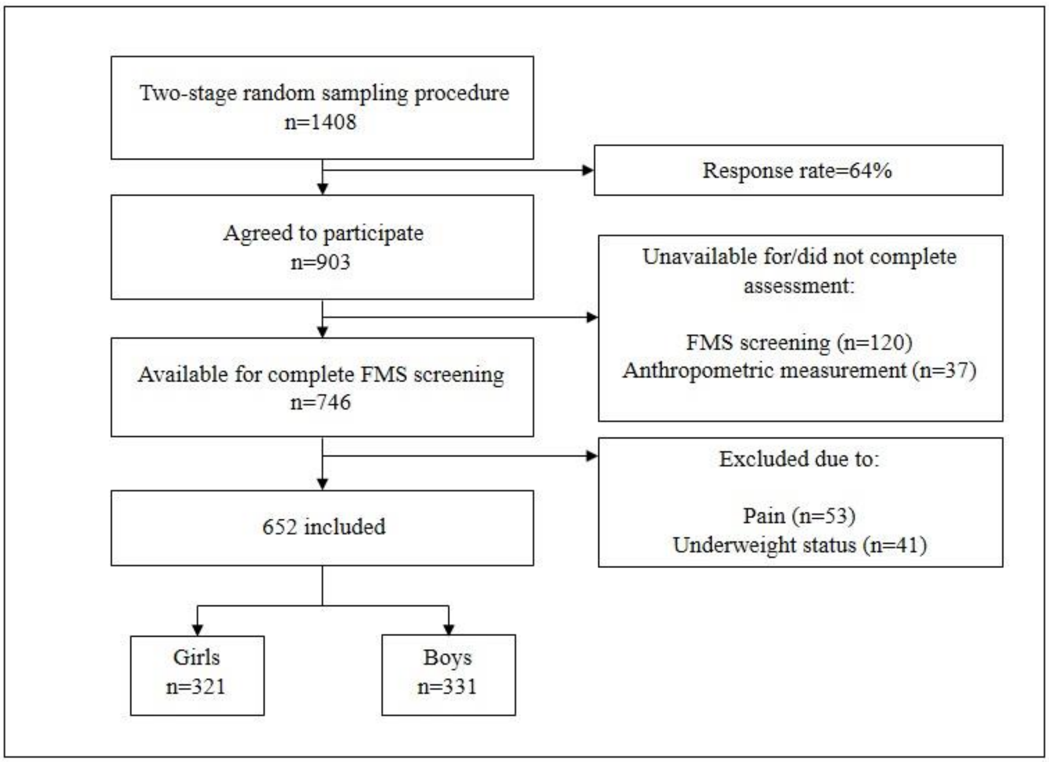

Figure 1. Flowchart of included participants. Note: FMS screening = functional movement screening standardized procedure.

To examine if the representativeness of the CRO-PALS sample has been preserved in the subsample selected for FMS assessment, we compared 652 participants from the current study to the rest of the CRO-PALS participants. These analyses indicated comparable values of moderate-to-vigorous physical activity and sum of four skinfolds (p = 0.8 and p = 0.6, respectively), while values of BMI, waist circumference, and hip circumference were slightly different between the participants from the current study compared with the rest of participants (BMI: 22.3 vs. 20.7 respectively, $p < 0.001$; waist circumference: 72.8 vs. 71.0, respectively, $p = 0.008$; hip circumference: 97.8 vs. 95.9, respectively, $p = 0.002$).

Having fully informed the children and their parents about the aims of the study, its protocol, and the possible hazards and discomforts related to the procedures used, written consent was obtained from both children and their parents or legal guardians. The study was performed according to the Declaration of Helsinki and the procedures were approved by the Ethics Committee of the Faculty of Kinesiology, University of Zagreb (Croatia) (No: 1009-2014).

2.2. Procedures

2.2.1. Outcomes: Functional Movement Screen Variables

FM (i.e., movement quality) was assessed via FMS™. FMS™ is a screening instrument designed for evaluation of mobility and stability of the seven functional movement patterns through seven tests (26,27): the deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise (ASLR), trunk stability push-up, and rotary stability. According to previous research, two-hour education on using FMS™ is efficient to gain an optimal interrater and intrarater reliability (45). However, the FMS™ was performed by ten novice trained raters who participated in two-day training performed by an FMS™ certified practitioner. Additionally, two sessions were organized in order to gain the precision and consistency of rater's testing procedures. Each participant had a maximum of three trials for each FMS™ movement pattern. After that, the highest FMS™ score from the three trials was documented (26,27). Each test was scored on a three-point scale (1–3), with higher scores indicating better movement quality. Evidence suggest that pain can change control of the movement patterns (46). Therefore, participants were asked if they felt pain while performing each of the 7 FMS™ movement patterns. Following this, fifty-three participants felt pain during the FMS™ testing procedure, and were not included in the further analyses. In this study, we defined FM as the movement with a given score of 2 or 3 during FMS™ procedure.

Furthermore, a score of 1 was given when the participant was unable to perform movement due to the number of movement compensation present which reflects the DFM pattern (26–28). This means that score of 2 and 3 was an indicator of FM, whereas a score of 1 was an indicator of DFM for each of 7 individual FMS tests. In this way, we could calculate the number and proportion of participants that exhibited DFM in each of the 7 individual FMS tests. This was the basic step for analyzing the differences in the proportion of participants that performed DFM between children with normal weight and children with overweight and obesity for each of 7 individual FMS^{TM} tests (i.e., using chi-square tests). Besides, an overall composite score (total FMS score) was calculated with a total FMS score of 21 according to standardized guidelines reported in the literature (26,27). In this way, the total FMS score was set as a continuous outcome variable for the 2-way ANOVA and multilevel model regression analysis.

2.2.2. Predictors: Body Mass Index, Sum of Four Skinfolds, Waist and Hip Circumference

Participants were weighed barefoot in their shorts and T-shirts with a pre-calibrated portable digital scale to the nearest 0.1 kg. Height was taken to the nearest 0.1 cm using an anthropometer (GPM, Siber-Hegner & Co., Zurich, Switzerland). Then, body mass index (BMI) was calculated as the body weight in kilograms divided by the body height in meters squared (kg/m^2) (47). Age and sex-specific BMI cut-off points proposed by the International Obesity Task Force criteria were used to distinguish between children with normal weight and children with overweight and obesity (44). For the purpose of this study participants were separated into two weight status groups: normal weight and overweight and obese group of children. Skinfold measurements were taken on the right side of the body at the following sites to the nearest 0.2 mm using Harpenden skinfold calliper (British indicators, West Sussex, UK): (1) triceps-at the back of the upper arm, halfway between the acromion process and the olecranon process, (2) biceps-at the front of the upper arm; at the same level as the triceps, (3) subscapular-about 2 cm below the lower angle of the scapula; a diagonal fold, (4) suprailiac-at the iliac crest; in anterior axillary line plane. Sum of all four skinfold measures was taken as the measure of the subcutaneous tissue content. All skinfold measures were taken in triplicate and median values were used for analyses. Waist and hip circumferences were measured manually with non-stretchable tape in a transverse plane at the midpoint between the last rib and the iliac crest, and at the level of the largest lateral extension of the hips, respectively (48). Skinfold measurements and body circumferences on all participants were performed by a single, skilled lab technician.

2.2.3. Confounders: Moderate-To-Vigorous Physical Activity (MVPA), Socioeconomic Status (SES), and Age

Physical activity level was assessed with the computerized version of the School Health Action, Planning, and Evaluation System (SHAPES) questionnaire (49). Details about calculation of physical activity variables (i.e., Moderate-to-Vigorous Physical Activity-MVPA) are described in the literature (49). In the study done by Wong et al. (49), moderate correlation was reported between the MVPA assessed by SHAPES and the results obtained with accelerometer. In addition, results from the SHAPES questionnaire are comparable with other physical activity instruments for mid-adolescents since above-mentioned research showed moderate agreement for MVPA assessed by SHAPES questionnaire (49).

SES was estimated with the following question: “What do you think about your financial situation when you compare yourself to other peers? Think about how much you can afford.”, while the following answers were offered: 1—Much lower than average, 2—Lower than average, 3—Average, 4—Higher than average, 5—Much higher than average. Furthermore, in all further multilevel models chronological age was included as a confounder variable (reported in years). In all models, age was centered around the value 17 and coded as “Age-17”.

2.3. Data Analysis

First, descriptive analysis for adiposity and confounder variables was conducted for girls and boys separately. Second, to determine the differences between the group of children with normal weight and overweight and obesity in total FMS score, a two-way ANOVA was employed, using weight status and sex as fixed factors. Third, to examine the differences between the group of children with normal weight and overweight in the proportion of individuals who performed DFM, a chi-square test was employed for boys and girls separately. Lastly, multilevel modelling was used to examine the relationship between the variables of adiposity and total FMS score according to the literature (50).

In the current study, authors have applied multilevel modelling methodology in three distinctive steps. First step included building the model at level one (first model). After that, another model was built (second model) which represented end of the first step. Following this, likelihood ratio test (LR test) was used for comparison of these two models (end of second step). In the third step, the model with a better fit was chosen (end of the third step). After the aforementioned three-step process was conducted, a further model was built, and this process was repeated (from first to the third step). In order to get the final model, this procedure was iterative, which yielded in the number of various multilevel regression models. Lastly, the model with the best fit was chosen and presented as the final model (50) (Figure 2).

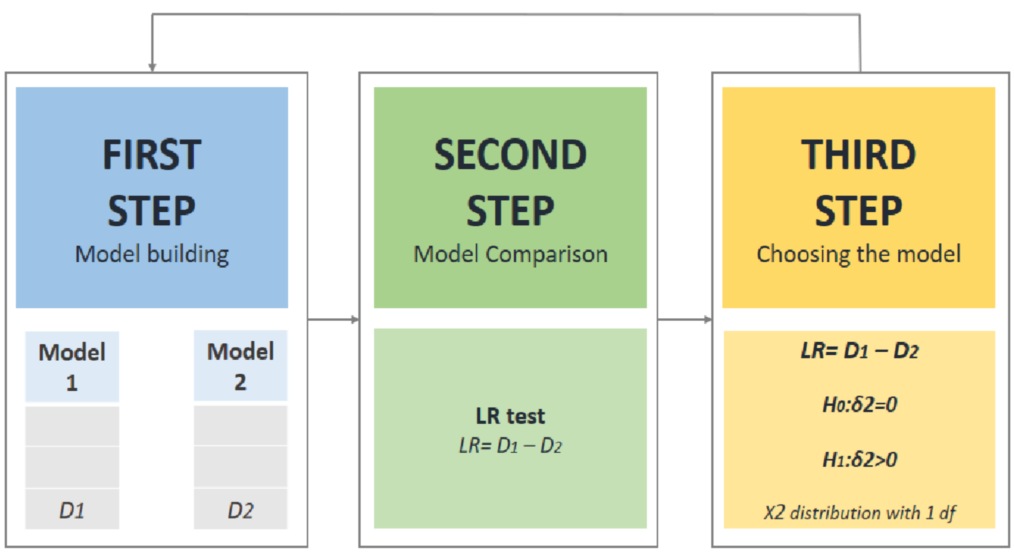

Figure 2. Three-step model building methodology.

According to the evidence, sex can affect weight status and total FMS score in the adolescent period (51). For this reason, all analyses were employed for each sex separately. In order to investigate association between different indicators of adiposity and FM, total FMS score was set as the response variable with the included BMI, the sum of four skinfolds, waist circumference, and hip circumference as predictor variables. Age, physical activity level, and SES were included in all models as the confounders since they have been previously shown to influence the total FMS score (20,52).

Results of descriptive statistics are shown as mean values _ SD. To perform multilevel analyses, MLwiN software (v. 3.04) (Centre for Multilevel Modelling, University of Bristol: Bristol, UK, 2019) was used (53). Furthermore, Statistica software (v. 13.5) (TIBICO Software Inc., Palo Alto, CA, USA) was employed to perform two-way ANOVA, while significance level was set at $p < 0.05$.

3. Results

3.1. Descriptive Statistics

Within the group of girls with overweight and obesity, eight girls were classified as girls with obesity (i.e., 15%), while within the group of boys with overweight and obesity, 17 boys (20%) were classified as boys with obesity. Table 1 presents the characteristics of the participants stratified by gender.

Table 1. Characteristics of the study sample stratified by gender.

Descriptive Characteristics	Girls (n = 321)	Boys (n = 331)
Age mean (SD)	16.6 (0.4)	16.7 (0.4)
OW & OB within each group n (%)	52 (16.2)	84 (25.4)
BMI (kg/m^2) mean (SD)	22.1 (3.0)	22.6 (3.4)
Sum of four skinfolds (mm) mean (SD)	49.9 (14.8)	37.1 (17.8)
Waist circumference (cm) mean (SD)	69.3 (6.2)	76.2 (7.3)
Hip circumference (cm) mean (SD)	97.5 (7.2)	98.1 (7.3)
MVPA (min/day) median (IQR)	85.7 (73.5)	117.9 (86.3)
SES median (IQR)	3 (1)	2 (1)

OW: overweight; OB: obesity; OW & OB within each group: Number (n) and percentage (%) of participants with overweight and obesity classified according to the International Obesity Task Force cut-offs within each sex group; BMI: Body Mass Index; MVPA: Moderate-to-Vigorous Physical Activity; SES: socio-economic status; IQR: Interquartile Range; SD: Standard Deviation.

3.2. Differences between Children with Normal Weight and Children with Overweight and Obesity in Total FMS Score

Results of 2-way ANOVA showed significant effect of sex (df = 1, F = 14.14, p = 0.00019), weight status (df = 1, F = 14.43, p = 0.00016), and sex * weight status interaction (df = 1, F = 8.81, p = 0.00016) on total FMS score. After that, Bonferroni's post-hoc test was performed and revealed a significant difference in total FMS score within the group of boys, where boys with normal weight surpass boys with overweight and obesity in total FMS score (12.6 and 11.1, respectively; p < 0.0001). Within the group of children with overweight and obesity, girls with overweight and obesity exhibited better results in total FMS score when compared with boys with overweight and obesity (12.6 vs. 11.1, respectively; $p < 0.0001$). Besides, the analysis showed significant interaction, where girls with normal weight outperformed boys with overweight and obesity (total FMS score: 12.8 vs. 11.1, respectively; $p < 0.001$). Results of 2-way ANOVA representing differences within sex and weight status group as well as the interaction between groups in total FMS score are presented in Table 2.

Table 2. Results of 2-way ANOVA representing differences within the sex and weight status group as well as the interaction between groups in total FMS score.

Sex/Weight Status Group	NW	OW & OB	Within Sex Group Difference	Interaction
Girls	12.8	12.6	p= 1.00	p= 1.00 [1]
Boys	12.6	11.1	p< 0.0001	p< 0.001 [2]
within weight status group difference	p= 1.00	p< 0.0001		

OW: overweight; OB: obesity; NW: Group of children with normal weight status; OW & OB: Group of children with overweight and obesity; Interaction: [1] p-value for the difference between group of boys with NW and group of girls with OW & OB; [2] p-value for the difference between group of girls with NW and boys with OW &OB; Post-hoc results were obtained using the Bonferroni post-hoc test.

3.3. Differences between Children with Normal Weight and Children with Overweight and Obesity in the Proportion of Individuals That Performed DFM in Each FMS Test

Differences in the proportion (%) of girls with normal weight and girls with overweight and obesity that performed DFM in each FMS test are shown in Figure 3. Interestingly, girls with normal weight showed a lower proportion of DFM compared to girls with overweight and obesity in only one FMS test—shoulder mobility (21% vs. 39%, respectively; $p = 0.04$).

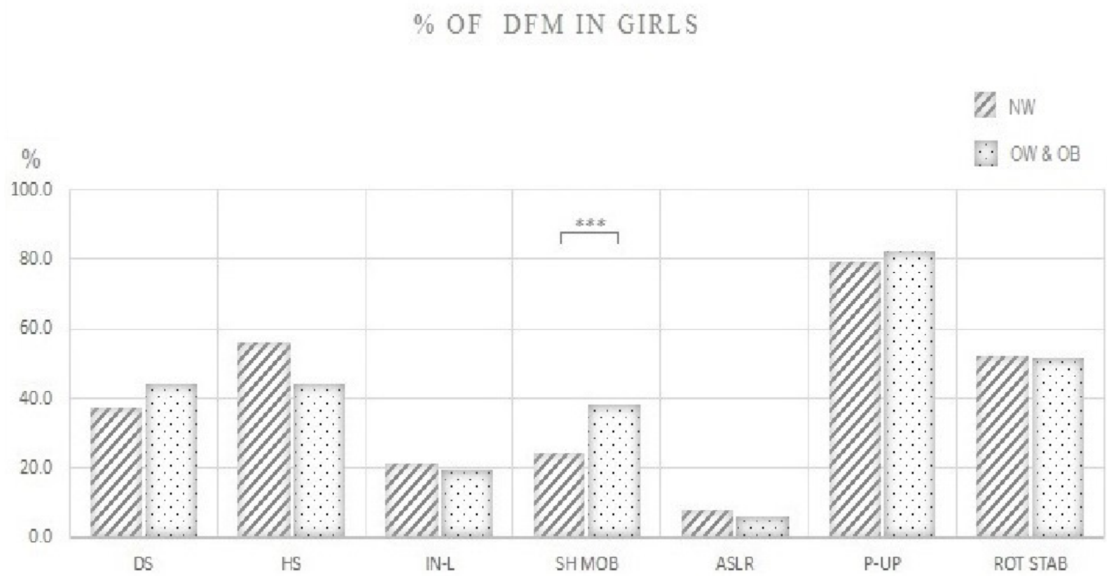

Figure 3. Proportion (%) of girls with normal weight and girls with overweight and obesity that performed dysfunctional movement (DFM) in each FMS test. Note: % OF DFM IN GIRLS: Proportion (%) of girls that performed dysfunctional movement; NW: Girls with normal weight; OW & OB: Girls with overweight and obesity; DS: Deep squat; HS: Hurdle step; IN-L: Inline lunge; ASLR: Active straight leg raise; SHO MOB: Shoulder mobility; P-UP-: Trunk stability push-up; ROT STAB: Rotary stability. *** *p* = 0.04.

Figure 4 demonstrates differences in the proportion (%) of boys with normal weight and boys with overweight and obesity that performed DFM in each FMS test. Boys with normal weight exhibited better quality of movement and lower proportion of DFM compared to boys with overweight and obesity in most of the FMS tests: deep squat (30% vs. 51%, respectively; $p < 0.0001$), inline lunge (29% vs. 43%, respectively; $p < 0.0001$), shoulder mobility (41% vs. 59%, respectively; $p = 0.01$), trunk stability push-up (33% vs. 62%, respectively; $p < 0.0001$), and rotary stability (32% vs. 59%, respectively; $p < 0.0001$).

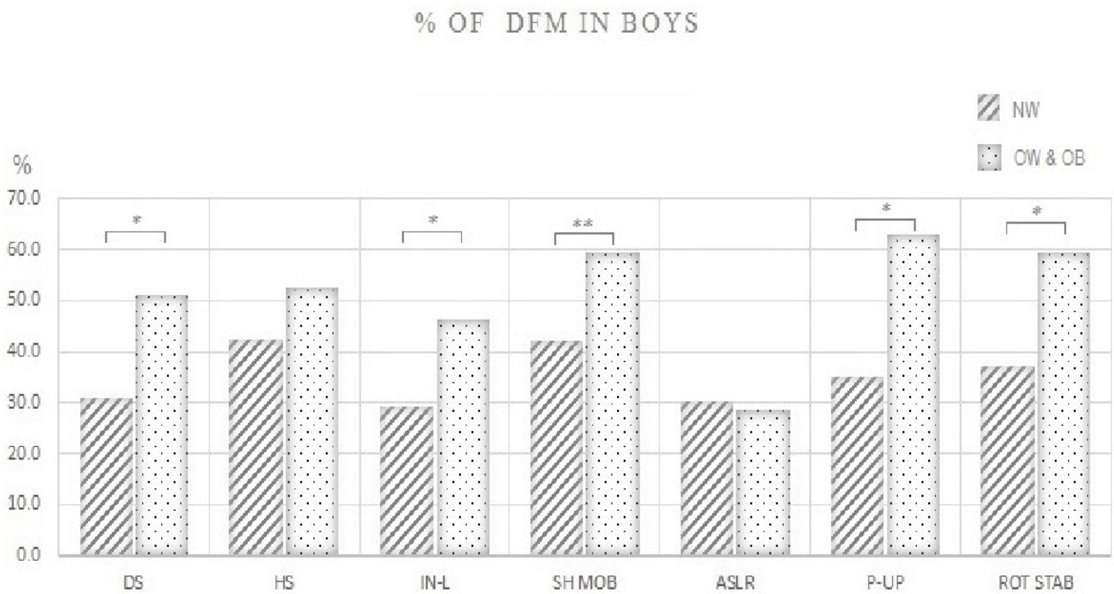

Figure 4. Proportion (%) of boys with normal weight and boys with overweight and obesity that performed dysfunctional movement (DFM) in each FMS test. Note: % OF DFM IN BOYS: Proportion (%) of boys that performed dysfunctional movement; NW: Boys with normal weight; OW & OB: Boys with overweight and obesity; DS: Deep squat; HS: Hurdle step; IN-L: Inline lunge; ASLR: Active straight leg raise; SHO MOB: Shoulder mobility; P-UP: Trunk stability push-up; ROT STAB: Rotary stability. * $p < 0.0001$, ** $p = 0.01$.

3.4. Relationship between the Variables of Adiposity and Total FMS Score

Since this study investigated high school children, in the current research, students were at level-1, clustered within classes at level-2 nested within schools at level-3, indicating that data have level-three hierarchical structure. In order to know how much clustering there is in our data, the variation partition coefficient (VPC) was calculated. Significant clustering among both sexes was seen (girls: VPC = 0.919; boys: VPC = 0.865), indicating that 8.1% and 13.5% of total FMS score variation lies within classes, and 91.9% and 86.5% of variation lies between girls and boys, respectively. When VPC is represented as an intraclass correlation coefficient (ICC), the correlation in total FMS score within classes among girls is 0.09, and 0.13 among boys; suggesting that there is non-independence in our dataset (see Appendix A, Figure A1). Level-3 deviance (D3) dropped when the level-3 model was introduced (D3 dropped by 0.25 in girls, and 0.6 in boys); and the level 3model was therefore not significant (among girls: LR = D2–D3 = 1460.567 –1460.317 = 0.25; among boys: LR = D2–D3 = 1520.92–1520.32 = 0.6). However, deviance at level-2 (D2) dropped significantly among both sexes (among girls: LR = D1–D2 = 1460.145–1460.567 = 5.78; among boys: LR = D1–D2 = 1534.85–1520.92 = 13.93). The quantile-quantile plots demonstrated an approximately straight line, implicating that normality assumption was reasonable (both at level-2 and level-1) among girls and boys.

After the initial investigation of hierarchical data, the three-step multilevel modeling approach was carried on as described in Section 2.3 Data Analysis (see also Figure 2). The random-intercept model was built first and included one of the predictors (e.g., BMI) with confounders: age, MVPA, and SES. Next, for each of the predictor variables (e.g., BMI), the random-slope model was introduced. Following this, LR test was used to compare aforementioned models and to choose the model with a better fit (50). At the end, predictor coefficients were modeled as random at level-2. Accordingly, separate analysis was done for each of the predictors which yielded in eight separate analyses (see Table 3). The coefficients shown in the tables are mean unstandardized coefficients (β) representing association between total FMS score and the different predictors. Although the addition of the confounders did not improve the models, nonsignificant confounders were retained in the models since they can influence the predictor coefficient (54).

Table 3. Relationship between variables of adiposity and total FMS score among girls and boys.

Response	**Total FMS Score**											
Predictor	**BMI**			**Sum of Four Skinfolds**			**Waist Circumference**			**Hip Circumference**		
Parameter	β	**S.E.**	***p***	β	**S.E.**	***p***	β	**S.E.**	***p***	β	**S.E.**	***p***
Girls	−0.05	0.04	0.23	**−0.03**	**0.01**	**0.0001**	−0.04	0.02	0.06	−0.01	0.02	0.70
Boys	**−0.18**	**0.04**	**0.0001**	**−0.04**	**0.01**	**0.0001**	**−0.08**	**0.02**	**0.0001**	**−0.09**	**0.02**	**0.0001**

Total FMS score: total Functional Movement Screen score; BMI: Body Mass Index; β: beta unstandardized coefficient; S.E.: Standard Error; *p*: *p*-value. All models are adjusted for age (centered around the value of 17), MVPA, and SES; The bold are significant results.

3.4.1. Association between Indicators of Adiposity and Total FMS Score among Girls

First, as a part of the multilevel approach, correlation analysis between BMI, the sum of four skinfolds, waist circumference, hip circumference, and total FMS score were employed separately. Results showed significant relationship between total FMS score and sum of four skinfolds ($r = -0.199$, $p < 0.0001$), while relationship with other predictors failed to reach significance (BMI: $r = -0.05$, $p = 0.353$; waist circumference: $r = -0.095$, $p = 0.091$; hip circumference: $r = -0.0075$, $p = 0.894$) (see Appendix A, Figure A2). After that, multilevel approach was employed. In the evaluation of the association between different adiposity predictors and total FMS score, level-2 random-intercept models were chosen as the models with the best fit in girls. When the models were controlled for chronological age, MVPA, and SES, only the sum of four skinfolds showed a significant association with the total FMS score ($\beta = -0.03$, $p < 0.0001$), while the coefficient for waist circumference approached significance ($\beta = -0.04$, $p = 0.06$). On the other hand, coefficients for BMI and hip circumference failed to reach significance ($\beta = -0.05$, $p = 0.23$; $\beta = -0.01$, $p = 0.70$, respectively) (Table 3).

3.4.2. Association between Indicators of Adiposity and Total FMS Score among Boys

Within the group of adolescent boys, correlation analysis showed significant relationship between total FMS score and all predictors (BMI: $r = -0.2596$, $p < 0001$; sum of four skinfolds: $r = -0.327$, $p < 0.0001$; waist circumference: $r = -0.2639$, $p = 0.0001$; hip circumference: $r = -0.2775$, $p = 0.0001$) (see Appendix A, Figure A3). Following this, the evaluation of the association between BMI, the sum of four skinfolds, waist and hip circumferences with total FMS score, yielded in level-2 random-intercept models as the models with the best fit. When the models were controlled for age, MVPA, and SES, all predictors demonstrated significant associations with total FMS score (BMI: $\beta = -0.18$, $p < 0.0001$; sum of four skinfolds: $\beta = -0.04$, $p < 0.0001$; waist circumference: $\beta = -0.08$, $p < 0.0001$; hip circumference: $\beta = -0.09$, $p < 0.0001$) (see Table 3). For instance, in the aforementioned multilevel analysis of the association between total FMS score and BMI in boys, BMI coefficient was −0.18 and it is shared by all school classes. The above-mentioned results can be interpreted as following: "increment of 5-point in BMI corresponds to a near to 1-point decrease in total FMS score among boys, holding other confounding variables constant".

4. Discussion

To our knowledge, this is the first study that has analyzed sex differences in FM between children with normal weight and children with overweight and obesity in the mid-adolescent period. The strength of our approach is seen in large sample size, separate analyses of girls and boys, control of known confounding variables (i.e., age, physical activity level, and SES), and the use of several variables of adiposity in analyses. The key findings of the present study are related to: (a) sex-specific differences in total and individual FMS scores between mid-adolescents with normal weight and mid-adolescents with overweight and obesity, and (b) generally low, but sex-specific, relationship between variables of adiposity and total FMS score in mid-adolescents.

Performance of our participants in FMS was comparable to 13–18-year old high-school athletes (55), but lower than those of Indian adolescents recreationally or competitively participating in sports (51); however, the studied sample in the latter study had a much wider age range (i.e., 10–17 years). Given that age and maturity status could have a significant effect on the FMS score (56), it could be a plausible reason for the observed discrepancy in findings. In the present study, we did not observe practically relevant sex differences in total FMS score, considering the total sample. This is in contrast to findings obtained on recreational or competitive adolescent athletes (51,57), where boys significantly outperformed girls in total FMS score (mean difference: 0.8–1.5). Thus, it seems that, at least in adolescents, sports participation could significantly affect sex-related differences in total FMS score.

In the current study, boys with overweight and obesity, but not girls, had significantly lower total FMS score compared to their peers with normal weight, suggesting that the association between adiposity and movement quality in mid-adolescents could be sex-specific. This finding is reinforced by the results of multilevel analyses, which showed a statistically significant relationship between variables of adiposity and total FMS score in boys, but not in girls. A previous study conducted by Duncan et al. (19) reported significantly lower FMS scores in overweight/obese group vs. normal weight group of school children (7–10 yo), but did not include a separate analysis for each sex. To date, only one study examined sex dimorphism in regards to adiposity and FM and did not reveal a sex difference in total FMS score within group of children with normal weight, overweight or obesity (34). Furthermore, the same study did not report a significant difference in total FMS score between group of boys with normal weight and overweight, which is contrary to results reported in the current study. It should be noted that a higher proportion of children with obesity was higher among boys compared to girls in the current study which could partly drive sex differences noted here. However, these findings are difficult to compare since the previously mentioned study included much younger participants (9.6 ± 1.5 yo) with a larger age span (6–13 yo) (34). Overall, our results suggest, for the first time, that sex is significantly associated with the movement proficiency and variables of adiposity in children and mid-adolescents.

There are two possible explanations behind the observed sex-specific relationship between adiposity and movement quality in mid-adolescents. (1) Neuromechanical: Evidence shows that adolescent boys are more prone to develop postural misalignment, such as hyperkyphosis compared to girls (16,58); since kyphotic posture decreases concentric activity of the thoracic paraspinal muscles, this could directly limit shoulder mobility test whereas this movement pattern requires active thoracic extension (i.e., demands concentric action of the paraspinal thoracic extensors muscles) (26–28). Moreover, hyperkyphosis can directly limit the optimal performance of the squat, inline lunge, and rotary stability since these patterns demand maintaining neutral spine position and co-contraction of the paraspinal thoracic muscles (26–28). Furthermore, flat feet are mostly seen in boys with overweight rather than in girls with overweight (59), which can cause deficits in uni- and contra- lateral lower-extremity stability movement patterns (i.e., in-line lunge and hurdle step) (26–28). Furthermore, adolescent boys with obesity demonstrate impairment of the rectus femoris muscle activation which is recruited while performing lower extremities movement patterns (60). (2) Physiological: Sex-specific association between adiposity and movement quality is likely to be the result of the maturation process, which differs between girls and boys and may have different impacts on movement proficiency during childhood and adolescence (61). Looking altogether, deficits which arose from each FMS^{TM} test resulted in decrease of the total FMS score among boys, but not girls. In the present study, regardless of the measure of adiposity used, common variance between adiposity and total FMS score did not exceed 10%. Previous studies have reported considerably larger inverse associations between BMI and FMS scores then in the current study (r ranged from −0.3 to −0.81) (19,20,34,40,41). Notably, several studies have reported that the strength of the association between BMI and motor coordination declines as children start to reach puberty

(62,63), which might explain some of the above-mentioned disparity in findings between the current and previous research.

Although our results shed some new light on the association of adiposity and movement quality of mid-adolescents, measured with the total FMS score, this approach could be methodologically limited, primary because of the poor factorial validity of the total FMS score. Several exploratory factor analyses of individual FMS tests have consistently reported in both youth and adults that the 7 tasks of FMS^{TM} have low internal consistency and were not indicators of a single factor (64–66). Indeed, a 2-factor structure of individual FMS scores has been always observed, with extracted factors explaining only 38–47% of the variance of all 7 FMS^{TM} tests, and with inconsistent and non-interpretable factor structure among different populations. As a result, the sum score of all FMS^{TM} tests does not represent a consistent and valid measure of human movement quality. This is particularly problematic during growth and maturation when differentiation of general movement coordination and motor qualities are occurring (55).

When the focus is shifted to individual FMS^{TM} tests, the limitation of particular tests, and consequently, the total FMS score to discriminate adolescents of different body size or composition becomes obvious. First, both our and several previous studies (51,55,57) have shown that female participants exhibit the worst performance in trunk stability push up, which is essentially a trunk and upper-body strength test, not a trunk stabilization test. In our case, 80% of girls with normal weight failed to perform trunk stability push up correctly, suggesting that the test was too difficult even for girls with normal body weight (Figure 3). Second, ASLR, which is essentially a flexibility test of the posterior leg, was too easy for adolescent girls, as only about 5% of them had a dysfunctional pattern in that test (Figure 3). As a result, both tests failed to contribute to the discriminatory power of the total FMS score when comparing adolescent girls with different body compositions. Of the remaining five FMS^{TM} tests, only the shoulder mobility test significantly discriminated adolescent girls with normal weight and girls with overweight. Notwithstanding the possibility that movement quality in adolescence is indeed less affected by adiposity in females, results of this large cross-sectional study question the usefulness of some FMS^{TM} tests in assessing movement quality of adolescent girls. In contrast, in boys, 5 out of 7 FMS^{TM} tests discriminated between those with normal weight and those with overweight and obesity (Figure 4).

Still, the general question remains: "How could overweight and obesity contribute to nonoptimal movement quality and what are the potential consequences of DFM in mid-adolescence period?".

The possible answer could give a concept which is modified according to the model proposed by Page et al. (67). This modified concept (i.e., model of musculoskeletal dysfunction cycle and contribution of obesity in the potential development of DFM patterns) consists of the seven stages (Figure 5). Evidence shows that higher body weight puts additional load on the joints (36), which, along with the sedentary behaviour and physical inactivity, can create muscle imbalances in overweight children (60) (stage 1) and lead to poor postural control (35) (stage 2). Compromised posture is associated with DFM patterns in overweight children (33) (stage 3). These DFM obesity-associated patterns could result in faulty motor program (stage 4) and altered proprioception (stage 5) with possible long-term consequences on musculoskeletal health, mainly joint degeneration (37) (stage 6) and body pain (stage 7). All aforementioned stages are presented as the separate elements within the presented model, where DFM, obesity, and gender could hypothetically play a significant role for the development of the postural pathologies in mid-adolescents. Accordingly, the current study could add the important piece of information within this cycle. However, further longitudinal and intervention studies are required to investigate impact of obesity on FM and musculoskeletal health in mid-adolescent population. Inclusive, both overweight and obesity negatively affect the quality of FM in mid-adolescents which could impact musculoskeletal health later in life. Therefore, exercise interventions that target both obesity and DFM needs to be incorporated into youth physical activity programs, school's curriculum, and youth sports.

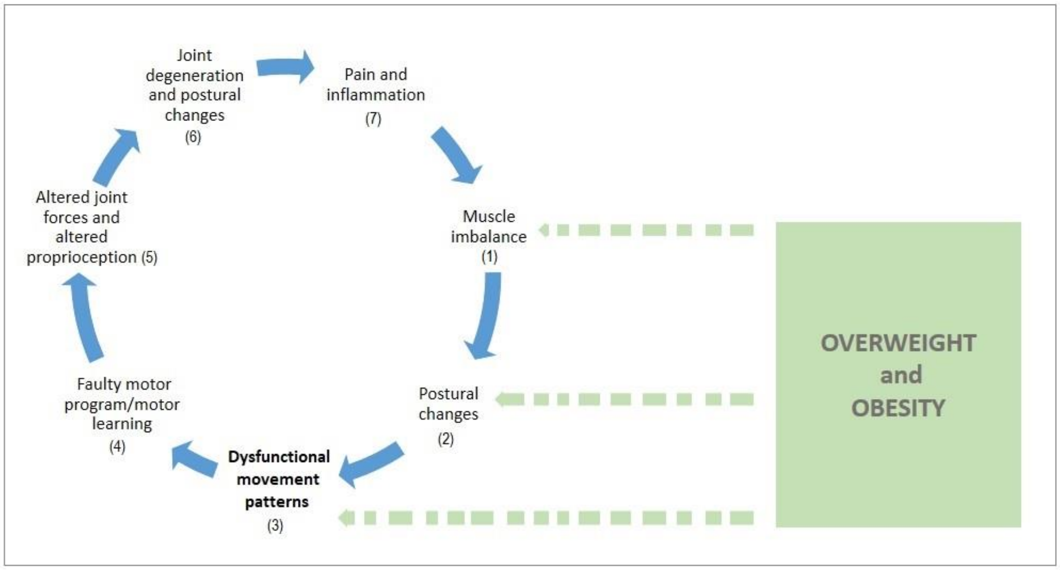

Figure 5. Model of musculoskeletal dysfunction cycle and contribution of obesity in the potential development of DFM patterns (modified according to Page et al., 2010).

Strengths and Limitations

There are many key strengths of current research that should be pointed out. To the best of the authors knowledge, this is the only research that has examined the association between FM (i.e., movement quality) and adiposity in the general population of mid-adolescents. Second, a large, age-homogeneous sample of mid-adolescents were recruited in this research (n = 652). Third, this is the first study that has employed the multilevel modelling for prediction of the FM through different indicators of adiposity in the population of mid-adolescents. This approach led to less biased conclusions. Fourth, this is the only research that has investigated relationship between adiposity variables and FM in mid-adolescent for boys and girls separately. This approach gave a new and valuable information about sex-specific relationships between FM and adiposity variables. Fifth, in this study adiposity was represented via four different indicators which can give deeper insight into relation between adiposity and FM. Last, this study controlled three common confounders which can yield in more precise forecast of FM (age, MVPA, and SES).

Furthermore, there are few limitations in this study. First, ten raters performed FMS^{TM} procedure which could affect consistency of the results. However, all ten raters went through uniform training on FMS^{TM} protocol, while recent evidence demonstrated good level of interrater agreement in the FMS^{TM} scores (45,68). Furthermore, a higher proportion of children with obesity among boys compared to girls, could drive some of the sex differences in the association of adiposity and FM reported here. However, given that this is a population-based study, this sex-difference in obesity rate was expected because they are based on the available data from the recent collation of representative studies in Croatian mid-adolescents (69). Lastly, participants from an urban area were recruited, while excluding rural mid-adolescents, which can influence generalizability of the findings.

5. Conclusions

Up to this point, there are no studies that have examined the association between a variety of adiposity indicators and FM in the population of mid-adolescents. Therefore, results of the present study extent previous knowledge on another population. The current study presents novel data demonstrating that overweight and obesity could possibly have detrimental effect on movement quality, as assessed by the FMS^{TM}, in boys, but not girls. Of particular note, although FMS scores were poorer in boys with overweight compared to boys with normal weight, being overweight and obese did not appear to confer the same detriment on quality of movement in girls. This means that the association between adiposity and FM in adolescence is sex-specific, suggesting that boys with overweight and obesity could be more prone to develop dysfunctional movement patterns. Development of the optimal movement quality during adolescence is a crucial step towards improving musculoskeletal health among girls and boys with overweight and obesity. More precisely, exercise interventions directed toward correcting dysfunctional patterns should be, to some degree, sex-specific, targeting more boys with overweight and obesity than girls with overweight. However, practicing FM patterns in both girls and boys with overweight and obesity could be helpful in order to potentially reduce the injury risk and future development of the postural pathologies in course of the adulthood. Overall, the results of the current study provide important information on the potential negative impact of adiposity on movement quality in the population of average mid-adolescents. This information is particularly important for physical therapists and coaches in youth sport, physical education teachers, and those working in the public health sector.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

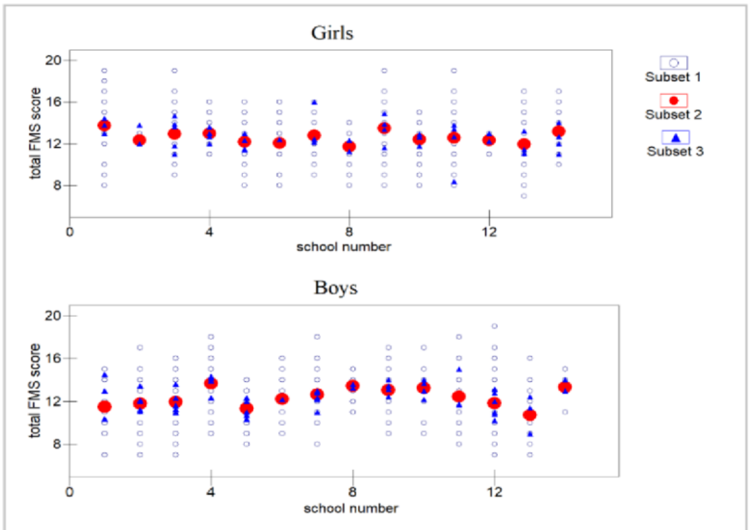

Figure A1. Total FMS score represented for each class and school (each school is represented with different number). Note: subset 1: students; subset 2: classes; subset 3: schools.

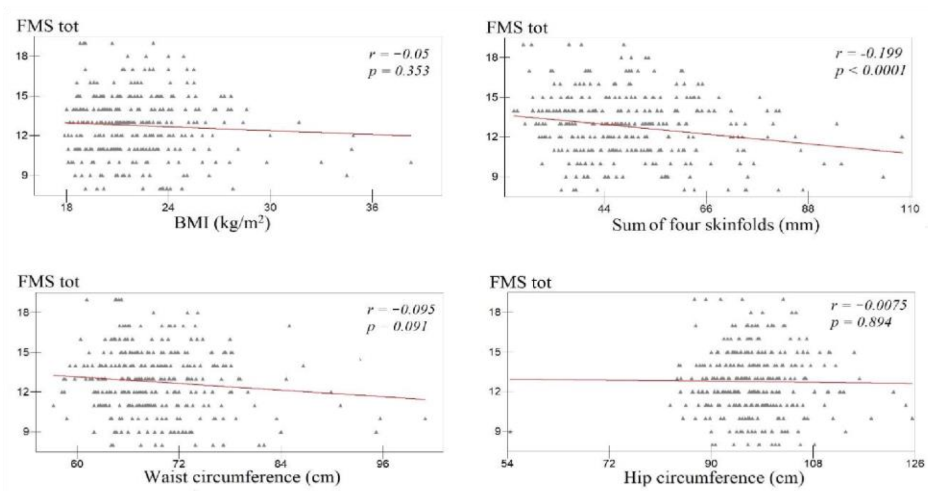

Figure A2. Correlation between BMI, sum of four skinfolds, waist and hip circumference, and total FMS score among girls.

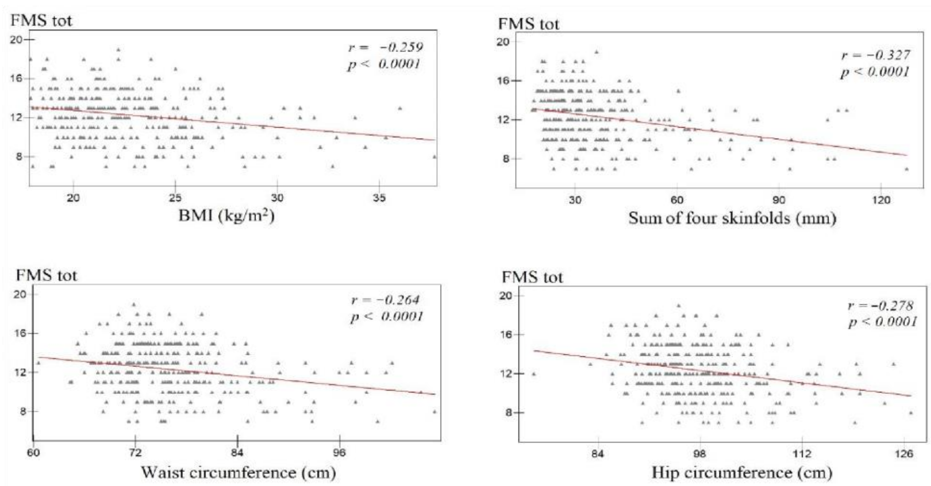

Figure A3. Correlation between BMI, sum of four skinfolds, waist and hip circumference and total FMS score among boys.

References

1. Merder-Coşkun, D.; Uzuner, A.; Keniş-Coşkun, Ö.; Çelenlioğlu, A.E.; Akman, M.; Karadağ-Saygi, E. Relationship between obesity and musculoskeletal system findings among children and adolescents. *Turk. J. Phys. Med. Rehabil.* **2017**, *63*, 207–214. [Google Scholar] [CrossRef]

2. Weihrauch-Blüher, S.; Schwarz, P.; Klusmann, J.H. Childhood obesity: Increased risk for cardiometabolic disease and cancer in adulthood. *Metabolism* **2019**, *92*, 147–152. [Google Scholar] [CrossRef]

3. Krul, M.; Van Der Wouden, J.C.; Schellevis, F.G.; Van Suijlekom-Smit, L.W.A.; Koes, B.W. Musculoskeletal problems in overweight and obese children. *Ann. Fam. Med.* **2009**, *7*, 352–356. [Google Scholar] [CrossRef]

4. Tsiros, M.D.; Tian, E.J.; Shultz, S.P.; Olds, T.; Hills, A.P.; Duff, J.; Kumar, S. Obesity, the new childhood disability? An umbrella review on the association between adiposity and physical function. *Obes. Rev.* **2020**, *12*, 26–36. [Google Scholar] [CrossRef]

5. Molina-Garcia, P.; Migueles, J.H.; Cadenas-Sanchez, C.; Esteban-Cornejo, I.; Mora-Gonzalez, J.; Rodriguez-Ayllon, M.; Plaza-Florido, A.; Vanrenterghem, J.; Ortega, F.B. A systematic review on biomechanical characteristics of walking in children and adolescents with overweight/obesity: Possible implications for the development of musculoskeletal disorders. *Obes. Rev.* **2019**, *20*, 1033–1044. [Google Scholar] [CrossRef]

6. Briggs, A.M.; Cross, M.J.; Hoy, D.G.; Sànchez-Riera, L.; Blyth, F.M.; Woolf, A.D.; March, L. Musculoskeletal Health Conditions Represent a Global Threat to Healthy Aging: A Report for the 2015 World Health Organization World Report on Ageing and Health. *Gerontologist* **2016**, *56*, S243–S255. [Google Scholar] [CrossRef]

7. Rosenfeld, S.B.; Schroeder, K.; Watkins-Castillo, S.I. The Economic Burden of Musculoskeletal Disease in Children and Adolescents in the United States. *J. Pediatr. Orthop.* **2018**, *38*, e230–e236. [Google Scholar] [CrossRef]

8. Kozak, A.; Schedlbauer, G.; Wirth, T.; Euler, U.; Westermann, C.; Nienhaus, A. Association between work-related biomechanical risk factors and the occurrence of carpal tunnel syndrome: An overview of systematic reviews and a meta-analysis of current research. *BMC Musculoskelet. Disord.* **2015**, *16*, 231. [Google Scholar] [CrossRef]

9. Mahmoud, N.F.; Hassan, K.A.; Abdelmajeed, S.F.; Moustafa, I.M.; Silva, A.G. The Relationship between Forward Head Posture and Neck Pain: A Systematic Review and Meta-Analysis. *Curr. Rev. Musculoskelet. Med.* **2019**, *12*, 562–577. [Google Scholar] [CrossRef]

10. Aderem, J.; Louw, Q.A. Biomechanical risk factors associated with iliotibial band syndrome in runners: A systematic review Rehabilitation, physical therapy and occupational health. *BMC Musculoskelet. Disord.* **2015**, *16*, 356. [Google Scholar] [CrossRef]

11. Boling, M.C.; Padua, D.A.; Marshall, S.W.; Guskiewicz, K.; Pyne, S.; Beutler, A. A prospective investigation of biomechanical risk factors for Patellofemoral pain syndrome: The joint undertaking to monitor and prevent acl injury (JUMP-ACL) Cohort. *Am. J. Sports Med.* **2009**, *37*, 2108–2116. [Google Scholar] [CrossRef] [PubMed]

12. Maciałczyk-Paprocka, K.; Stawińska-Witoszyńska, B.; Kotwicki, T.; Sowińska, A.; Krzyżaniak, A.; Walkowiak, J.; Krzywińska-Wiewiorowska, M. Prevalence of incorrect body posture in children and adolescents with overweight and obesity. *Eur. J. Pediatr.* **2017**, *176*, 563–572. [Google Scholar] [CrossRef] [PubMed]

13. Brzeziński, M.; Czubek, Z.; Niedzielska, A.; Jankowski, M.; Kobus, T.; Ossowski, Z. Relationship between lower-extremity defects and body mass among polish children: A cross-sectional study. *BMC Musculoskelet. Disord.* **2019**, *20*, 84. [Google Scholar] [CrossRef] [PubMed]

14. Araújo, F.A.; Martins, A.; Alegrete, N.; Howe, L.D.; Lucas, R. A shared biomechanical environment for bone and posture development in children. *Spine J.* **2017**, *17*, 1426–1434. [Google Scholar] [CrossRef] [PubMed]

15. Lonner, B.S.; Toombs, C.S.; Husain, Q.M.; Sponseller, P.; Shufflebarger, H.; Shah, S.A.; Samdani, A.F.; Betz, R.R.; Cahill, P.J.; Yaszay, B.; et al. Body Mass Index in Adolescent Spinal Deformity: Comparison of Scheuermann's Kyphosis, Adolescent Idiopathic Scoliosis, and Normal Controls. *Spine Deform.* **2015**, *3*, 318–326. [Google Scholar] [CrossRef] [PubMed]

16. Jankowicz-Szymańska, A.; Bibro, M.; Wodka, K.; Smola, E. Does excessive body weight change the shape of the spine in children? *Child. Obes.* **2019**, *15*, 346–352. [Google Scholar] [CrossRef]

17. Catan, L.; Amaricai, E.; Onofrei, R.R.; Popoiu, C.M.; Iacob, E.R.; Stanciulescu, C.M.; Cerbu, S.; Horhat, D.I.; Suciu, O. The impact of overweight and obesity on plantar pressure in children and adolescents: A systematic review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6600. [Google Scholar] [CrossRef]

18. Pill, S.; Harvey, S. A Narrative Review of Children's Movement Competence Research 1997–2017. *Phys. Cult. Sport. Stud. Res.* **2019**, *81*, 47–74. [Google Scholar] [CrossRef]

19. Duncan, M.J.; Stanley, M.; Leddington Wright, S. The association between functional movement and overweight and obesity in British primary school children. *Sport. Med. Arthrosc. Rehabil. Ther. Technol.* **2013**, *5*, 11. [Google Scholar] [CrossRef]

20. Duncan, M.J.; Stanley, M. Functional movement is negatively associated with weight status and positively associated with physical activity in British primary school children. *J. Obes.* **2012**, *2012*, 697563. [Google Scholar] [CrossRef]

21. Ahnert, J.; Schneider, W.; Bös, K. Developmental changes and individual stability of motor abilities from the preschool period to young adulthood. In *Human Development from Early Childhood to Early Adulthood: Evidence from the Munich Longitudinal Study on the Genesis of Individual Competencies (LOGIC)*, 1st ed.; Schneider, W., Bullock, M., Eds.; Psychology Press: New York, NY, USA, 2009; pp. 54–57. [Google Scholar]

22. Stodden, D.F.; Goodway, J.D.; Langendorfer, S.J.; Roberton, M.A.; Rudisill, M.E.; Garcia, C.; Garcia, L.E. A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship. *Quest* **2008**, *60*, 290–306. [Google Scholar] [CrossRef]

23. Bernardes Marques, V.; Menezes Medeiros, T.; de Souza Stigger, F.; Yuzo Nakamura, F.; Manfredini Baroni, B. The funcional Movement Screen (FMS^{TM}) in elite young soccer players between 14 and 20 years: Composite score, individual-test scores and asymmetries. *Int. J. Sports Phys. Ther.* **2017**, *12*, 977–985. [Google Scholar] [CrossRef]

24. Kraus, K.; Schütz, E.; Taylor, W.R.; Doyscher, R. Efficacy of the functional movement screen: A review. *J. Strength. Cond. Res.* **2014**, *28*, 3571–3584. [Google Scholar] [CrossRef] [PubMed]

25. Silva, B.; Rodrigues, L.P.; Clemente, F.M.; Cancela, J.M.; Bezerra, P. Association between motor competence and functional movement screen scores. *PeerJ* **2019**, *7*, e7270. [Google Scholar] [CrossRef]

26. Cook, G.; Burton, L.; Hoogenboom, B. Pre-Participation Screening: The Use of Fundamental Movements as an Assessment of Function–Part 1. *N. Am. J. Sport. Phys. Ther.* **2006**, *1*, 62–72. [Google Scholar]

27. Cook, G.; Burton, L.; Hoogenboom, B. Pre-Participation Screening: The Use of Fundamental Movements as an Assessment of Function–Part 2. *N. Am. J. Sport. Phys. Ther.* **2006**, *1*, 132–139. [Google Scholar]

28. Cook, G. *Movement: Functional Movement Systems: Screening, Asseessmnet and Corrective Strategies*, 1st ed.; Lottus Pub: Aptos, CA, USA, 2011; pp. 31–32. [Google Scholar]

29. Kiesel, K.B.; Butler, R.J.; Plisky, P.J. Prediction of Injury by Limited and Asymmetrical Fundamental Movement Patterns in American Football Players. *J. Sport Rehabil.* **2014**, *23*, 88–94. [Google Scholar] [CrossRef]

30. Shojaedin, S.S.; Letafatkar, A.; Hadadnezhad, M.; Dehkhoda, M.R. Relationship between functional movement screening score and history of injury and identifying the predictive value of the FMS for injury. *Int. J. Inj. Contr. Saf. Promot.* **2014**, *21*, 355–360. [Google Scholar] [CrossRef]

31. Bonazza, N.A.; Smuin, D.; Onks, C.A.; Silvis, M.L.; Dhawan, A. Reliability, Validity, and Injury Predictive Value of the Functional Movement Screen. *Am. J. Sports Med.* **2017**, *45*, 725–732. [Google Scholar] [CrossRef]

32. Garrison, M.; Westrick, R.; Johnson, M.R.; Benenson, J. Association between the functional movement screen and injury development in college athletes. *Int. J. Sports Phys. Ther.* **2015**, *10*, 21–28. [Google Scholar]

33. Molina-Garcia, P.; Plaza-Florido, A.; Mora-Gonzalez, J.; Torres-Lopez, L.V.; Vanrenterghem, J.; Ortega, F.B. Role of physical fitness and functional movement in the body posture of children with overweight/obesity. *Gait Posture* **2020**, *80*, 331–338. [Google Scholar] [CrossRef]

34. García-Pinillos, F.; Roche-Seruendo, L.E.; Delgado-Floody, P.; Mayorga, D.J.; Latorre-Román, P.Á. Original is there any relationship between functional movement and weight status. *Nutr. Hosp.* **2018**, *35*, 805–810. [Google Scholar] [CrossRef]

35. D'Hondt, E.; Deforche, B.; De Bourdeaudhuij, I.; Lenoir, M. Childhood obesity affects fine motor skill performance under different postural constraints. *Neurosci. Lett.* **2008**, *440*, 72–75. [Google Scholar] [CrossRef]

36. Gushue, D.L.; Houck, J.; Lerner, A.L. Effects of Childhood Obesity on Three-Dimensional Knee Joint Biomechanics during Walking. *J. Pediatr. Orthop.* **2005**, *25*, 763–768. [Google Scholar] [CrossRef]

37. Widhalm, H.K.; Seemann, R.; Hamboeck, M.; Mittlboeck, M.; Neuhold, A.; Friedrich, K.; Hajdu, S.; Widhalm, K. Osteoarthritis in morbidly obese children and adolescents, an age-matched controlled study. *Knee Surg. Sport. Traumatol. Arthrosc.* **2016**, *24*, 644–652. [Google Scholar] [CrossRef]

38. NCD Risk Factor Collaboration (NCD-RisC). Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: A pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *Lancet* **2017**, *390*, 2627–2642. [Google Scholar] [CrossRef]

39. Quatman-Yates, C.C.; Quatman, C.E.; Meszaros, A.J.; Paterno, M.V.; Hewett, T.E. A systematic review of sensorimotor function during adolescence: A developmental stage of increased motor awkwardness? *Br. J. Sports Med.* **2012**, *46*, 649–655. [Google Scholar] [CrossRef]

40. Molina-Garcia, P.; Migueles, J.H.; Cadenas-Sanchez, C.; Esteban-Cornejo, I.; Mora-Gonzalez, J.; Rodriguez-Ayllon, M.; Plaza-Florido, A.; Molina-Molina, A.; Garcia-Delgado, G.; D'Hondt, E.; et al. Fatness and fitness in relation to functional movement quality in overweight and obese children. *J. Sports Sci.* **2019**, *37*, 878–885. [Google Scholar] [CrossRef]

41. Nicolozakes, C.P.; Schneider, D.K.; Rower, B.; Borchers, J.; Hewett, T.E. Influence of Body Composition on Functional Movement Screen™ Scores in Collegiate Football Players. *J. Sport Rehabil.* **2017**, *27*, 431–437. [Google Scholar] [CrossRef]

42. Mitchell, U.H.; Johnson, A.W.; Adamson, B. Relationship between functional movement screen scores, core strength, posture, and body mass index in school children in moldova. *J. Strength Cond. Res.* **2015**, *29*, 1172–1179. [Google Scholar] [CrossRef]

43. Štefan, L.; Sorić, M.; Devrnja, A.; Podnar, H.; Mišigoj-Duraković, M. Is school type associated with objectively measured physical activity in 15-year-olds? *Int. J. Environ. Res. Public Health* **2017**, *14*, 1417. [Google Scholar] [CrossRef] [PubMed]

44. Cole, T.J.; Bellizzi, M.C.; Flegal, K.M.; Dietz, W.H. Establishing a standard definition for child overweight and obesity worldwide: International survey. *Br. Med. J.* **2000**, *320*, 1240–1243. [Google Scholar] [CrossRef]

45. Smith, C.A.; Chimera, N.J.; Wright, N.J.; Warren, M. Interrater and intrarater reliability of the functional movement screen. *J. Strength Cond. Res.* **2013**, *27*, 982–987. [Google Scholar] [CrossRef] [PubMed]

46. Sterling, M.; Jull, G.; Wright, A. The effect of musculoskeletal pain on motor activity and control. *J. Pain* **2001**, *2*, 135–145. [Google Scholar] [CrossRef] [PubMed]

47. Garrow, J.S.; Webster, J. Quetelet's index (W/H2) as a measure of fatness. *Int. J. Obes.* **1985**, *9*, 147–153. [Google Scholar] [PubMed]

48. WHO Expert Committee on Physical Status. *Physical Status: The Use and Interpretation of Anthropometry: Report of a WHO Expert Committee*; World Health Organization Technical Report Series; WHO: Geneva, Switzerland, 1995; pp. 263–306. [Google Scholar]

49. Wong, S.L.; Leatherdale, S.T.; Manske, S. Reliability and validity of a school-based physical activity questionnaire. *Med. Sci. Sports Exerc.* **2006**, *38*, 1593–1600. [Google Scholar] [CrossRef]

50. Rasbash, J.; Steele, F.; Browne, W.J.; Goldstein, H. *A User's Guide to MLwiN*; Centre for Multilevel Modelling, University of Bristol: Bristol, UK, 2019; Available online: http://www.bristol.ac.uk/cmm/ (accessed on 5 September 2020).

51. Abraham, A.; Sannasi, R.; Nair, R. Normative values for the functional movement screen™ in adolescent school aged children. *Int. J. Sports Phys. Ther.* **2015**, *10*, 29–36. [Google Scholar]

52. Lester, D.; McGrane, B.; Belton, S.; Duncan, M.J.; Chambers, F.C.; O'Brien, W. The Age-Related Association of Movement in Irish Adolescent Youth. *Sports* **2017**, *5*, 77. [Google Scholar] [CrossRef]

53. Charlton, C.; Rasbash, J.; Browne, W.J.; Healy, M.; Cameron, B. *MLwiN Version 3.04*; Centre for Multilevel Modelling, University of Bristol: Bristol, UK, 2019. [Google Scholar]

54. Skelly, A.; Dettori, J.; Brodt, E. Assessing bias: The importance of considering confounding. *Evid. Based Spine Care J.* **2012**, *3*, 9–12. [Google Scholar] [CrossRef]

55. Bardenett, S.M.; Micca, J.J.; DeNoyelles, J.T.; Miller, S.D.; Jenk, D.T.; Brooks, G.S. Functional Movement Screen Normative Values and Validity in High School Athletes: Can the Fms™ Be Used as a Predictor of Injury? *Int. J. Sports Phys. Ther.* **2015**, *10*, 303–308. [Google Scholar]

56. Portas, M.D.; Parkin, G.; Roberts, J.; Batterham, A.M. Maturational effect on Functional Movement Screen™ score in adolescent soccer players. *J. Sci. Med. Sport* **2016**, *19*, 854–858. [Google Scholar] [CrossRef] [PubMed]

57. Anderson, B.E.; Neumann, M.L.; Huxel Bliven, K.C. Functional movement screen differences between male and female secondary school athletes. *J. Strength Cond. Res.* **2015**, *29*, 1098–1106. [Google Scholar] [CrossRef] [PubMed]

58. Dolphens, M.; Cagnie, B.; Vleeming, A.; Vanderstraeten, G.; Danneels, L. Gender differences in sagittal standing alignment before pubertal peak growth: The importance of subclassification and implications for spinopelvic loading. *J. Anat.* **2013**, *223*, 629–640. [Google Scholar] [CrossRef]

59. Gijon-Nogueron, G.; Montes-Alguacil, J.; Martinez-Nova, A.; Alfageme-Garcia, P.; Cervera-Marin, J.A.; Morales-Asencio, J.M. Overweight, obesity and foot posture in children: A cross-sectional study. *J. Paediatr. Child Health* **2017**, *53*, 33–37. [Google Scholar] [CrossRef]

60. Blimkie, C.J.R.; Sale, D.G.; Bar-Or, O. Voluntary strength, evoked twitch contractile properties and motor unit activation of knee extensors in obese and non-obese adolescent males. *Eur. J. Appl. Physiol. Occup. Physiol.* **1990**, *61*, 313–318. [Google Scholar] [CrossRef]

61. Duncan, M.J.; Bryant, E.; Stodden, D. Low fundamental movement skill proficiency is associated with high BMI and body fatness in girls but not boys aged 6–11 years old. *J. Sports Sci.* **2017**, *35*, 2135–2141. [Google Scholar] [CrossRef]

62. D'Hondt, E.; Deforche, B.; De Bourdeaudhuij, I.; Lenoir, M. Relationship between motor skill and body mass index in 5- to 10-year-old children. *Adapt. Phys. Act. Q.* **2009**, *26*, 21–37. [Google Scholar] [CrossRef]

63. Lopes, V.P.; Stodden, D.F.; Bianchi, M.M.; Maia, J.A.R.; Rodrigues, L.P. Correlation between BMI and motor coordination in children. *J. Sci. Med. Sport* **2012**, *15*, 38–43. [Google Scholar] [CrossRef]

64. Li, Y.; Wang, X.; Chen, X.; Dai, B. Exploratory factor analysis of the functional movement screen in elite athletes. *J. Sports Sci.* **2015**, *33*, 1166–1172. [Google Scholar] [CrossRef]

65. Kazman, J.B.; Galecki, J.M.; Lisman, P.; Deuster, P.A.; O'Connor, F.G. Factor structure of the functional movement screen in marine officer candidates. *J. Strength Cond. Res.* **2014**, *28*, 672–678. [Google Scholar] [CrossRef]

66. Wright, M.D.; Chesterton, P. Functional Movement Screen TM total score does not present a gestalt measure of movement quality in youth athletes. *J. Sports Sci.* **2019**, *37*, 1393–1402. [Google Scholar] [CrossRef] [PubMed]

67. Page, P.; Frank, C.C.; Lardner, R. *Assessment and Treatment of Muscle Imbalance: The Janda Approach*, 1st ed.; Human Kinetics: Champaign, IL, USA, 2010; pp. 44–46. [Google Scholar]

68. Teyhen, D.S.; Shaffer, S.W.; Lorenson, C.L.; Halfpap, J.P.; Donofry, D.F.; Walker, M.J.; Dugan, J.L.; Childs, J.D. The Functional Movement Screen: A Reliability Study. *J. Orthop. Sport. Phys. Ther.* **2012**, *42*, 530–540. [Google Scholar] [CrossRef] [PubMed]

69. NCD Risk Factor Collaboration (NCD-RisC). Height and body-mass index trajectories of school-aged children and adolescents from 1985 to 2019 in 200 countries and territories: A pooled analysis of 2181 population-based studies with 65 million participants. *Lancet* **2020**, *396*, 1511–1524. [Google Scholar] [CrossRef]

Study 3: Can Injuries Be Predicted via Functional Movement Screen in Adolescents? The Application of Machine Learning

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Can Injuries Be Predicted by Functional Movement Screen in Adolescents? The Application of Machine Learning

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Abstract

Karuc, J, Mišigoj-Duraković, M, Šarlija, M, Marković, G, Hadžić, V, Trošt-Bobić, T, and Sorić, M. Can injuries be predicted by functional movement screen in adolescents? The application of machine learning. J Strength Cond Res, 2021. *Advance online publication* —This study used machine learning (ML) to predict injuries among adolescents by functional movement testing. This research is a part of the CRO-PALS study conducted in a representative sample of adolescents and analyses for this study are based on nonathletic (n=364) and athletic (n=192) subgroups of the cohort (16–17 years). Sex, age, body mass index (BMI), body fatness, moderate-to-vigorous physical activity (MVPA), training hours per week, Functional Movement Screen (FMS), and socioeconomic status were assessed at baseline. A year later, data on injury occurrence were collected. The optimal cut-point of the total FMS score for predicting injury was calculated using receiver operating characteristic curve. These predictors were included in ML analyses with calculated metrics: area under the curve (AUC), sensitivity, specificity, and odds ratio (95% confidence interval [CI]). Receiver operating characteristic curve analyses with associated criterium of total FMS score .12 showed AUC of 0.54 (95% CI: 0.48–0.59) and 0.56 (95% CI: 0.47–0.63), for the nonathletic and athletic youth, respectively. However, in the nonathletic subgroup, ML showed that the Naïve Bayes exhibited highest AUC (0.58), whereas in the athletic group, logistic regression was demonstrated as the model with the best predictive accuracy (AUC: 0.62). In both subgroups, with given predictors: sex, age, BMI, body fat percentage, MVPA, training hours per week, socioeconomic status, and total FMS score, ML can give a more accurate prediction then FMS alone. Results indicate that nonathletic boys who have lower-body fat could be more prone to suffer from injury incidence, whereas among athletic subjects, boys who spend more time training are at a higher risk of being injured. Conclusively, total FMS cut-off scores for each subgroup did not successfully discriminate those who suffered from those who did not suffer from injury, and, therefore, our research does not support FMS as an injury prediction tool.

Key Words: artificial intelligence, AI, movement quality, adolescence, forecasting injury, musculoskeletal conditions

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1. Introduction

Musculoskeletal injuries and conditions represent a major public health problem, with significant social, economic, and health consequences (42,50). Indeed, impaired proprioception, muscle weakness, poor balance and joint instability, limited range of motion, and persistent pain have been frequently observed after musculoskeletal injury (1,24,25,29,31). A recently published systematic review has showed that changes in the range of motion that occur during the progress through adolescence and growth spurts may lead to an increase in injury incidence as well (59). Adolescence has been shown repeatedly to be the most sensitive period for higher injury vulnerability (18,47,67,70). Therefore, it is of crucial importance that the hierarchy of responsibility for injury incidence is well established in the adolescent population (20). Thus, effective preventive injury strategies should be incorporated across sports clubs and schools. In adolescence, various factors can contribute to higher injury risk such as previous injury, sports participation, high body mass index (BMI), total body fat, and others (19,21,32). These factors have been well studied, but none of these studies considered movement quality to be one of the predictive factors for injury in average adolescents. On the other hand, there are more and more studies that investigate movement quality and functional movement among athletic youth (43). Furthermore, several studies suggested functional movement quality to be one of the potential predictive factors of injury in young and adult athletes (28,34,35,45,55). The most commonly used diagnostic tool to assess the risk of injury through movement quality is the Functional Movement Screen (FMS) (69). Functional Movement Screen is a screening tool that evaluates functional movement quality by examining 7 fundamental movement patterns (12,13). Although there is conflicting evidence for FMS injury prediction value (28,34,36,43,55), it has been widely used among practitioners all over the world. Therefore, its predictive ability needs to be well established across different populations and groups. Scientists interested in studying the quality of movement across in different populations is constantly growing (17,43,64,69).

However, to this date, the prediction of musculoskeletal injury by FMS in the average adolescent population has not been investigated.

At the same time, in the last decade, machine learning (ML), as a form of artificial intelligence (AI), has found application across a diverse array of scientific branches (41). For example, it has been shown that ML can successfully predict various outcomes in the medical field (37,53). Because it is still at the beginning of the use in sport science (9), only few studies used ML methodology to predict injury in an adult population of athletes (14,38,51,52,62,72). However, no studies have attempted to use ML for injury prediction in the general adolescent population. To the best of our knowledge, this is the first study that attempted to predict injuries by functional movement quality in a 1-year period by using ML in the adolescent population. Therefore, the aim of this study is to investigate whether FMS alone or in combination with other predictors supported with ML methodology would give a better injury prediction model for a 1-year period in a representative sample of urban adolescents (nonathletic and athletic subjects).

2. Methods

2.1. Experimental Approach to the Problem

This was a prospective study that included a representative sample of urban adolescents (athletic and nonathletic subjects). This research attempted to determine the optimal FMS cut-off point that could predict injury occurrence in a 1-year period among athletic and nonathletic subjects. In addition, ML methodology was used to build a model that could successfully predict injury occurrence among athletic and nonathletic subjects. Sex, age, BMI, body fatness, moderate-to-vigorous physical activity (MVPA), training hours per week, FMS, and socioeconomic status were assessed at baseline and were included as predictors in ML modeling afterward. One year after baseline measurement, data on injury occurrence were collected.

2.2. Subjects

This research is a part of the CRO-PALS study, which is an observational, 4-year longitudinal study conducted in a representative sample of urban youth in Zagreb (Croatia). Details on the sampling and procedures of the study have been described elsewhere (60). In brief, using stratified 2-stage random sampling procedures (school level and class level), 54 classes in 14 secondary schools in Zagreb were selected to participate in the study. All 1,408 students in the selected classes were approached, and 903 agreed to participate (response rate = 64%). Because 120 subjects were unavailable on the day of testing or did not complete the FMS testing procedure, for the purpose of this study, we collected data from 783 adolescents (mean age ± SD = 16.6 ± 0.4 years).

Baseline measurements were performed during spring in 2015 and included information on age, sex, functional movement, pain, sports participation, socioeconomic status, physical activity (PA) level, BMI, and body fatness. All subjects were screened by a medical doctor and were excluded if they (a) had any pain while movement screening and (b) had acute medical condition that precluded FMS testing (neurologic disorders or serious orthopedic trauma such as bone fractures or complete muscle ruptures). Accordingly, 53 subjects were excluded, and 5 subjects did not provide information about sports participation; therefore, the total number of subjects at baseline was 725. In the next wave of assessments, in the spring of 2016, data on the epidemiology of injuries suffered during the past year were gathered. In the next step, subjects who reported nonrelated musculoskeletal injuries (i.e., head trauma, oral injuries, etc.) (n = 31) and subjects whose injuries were unrelated to PA (n = 65) were excluded. In addition, 73 subjects dropped out from the study. Therefore, the total number of children who were analyzed was 556 (age range: 15.6 – 18.3 years). After that, for the purpose of this research, the sample was divided into the athletic (n = 192) and nonathletic group (n = 364).

The flowchart of the included subjects is shown in Figure 1. Having fully informed the children and their parents about the aims of the study, its protocol, and the possible hazards and discomforts related to the procedures used, written consent was obtained from both children and their parents or legal guardians. The study was performed according to the Declaration of Helsinki, and the procedures were approved by the Ethics Committee of the Faculty of Kinesiology, University of Zagreb, Croatia (No: 1009-2014).

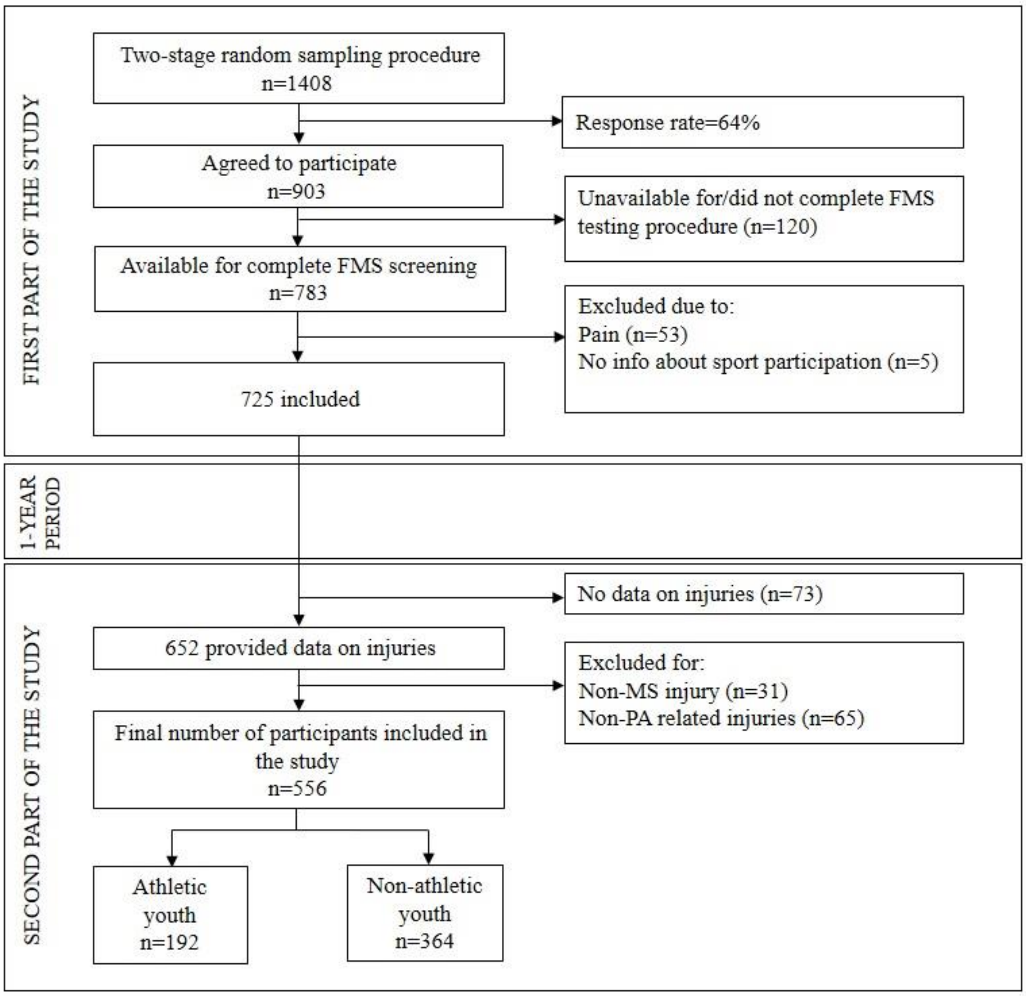


Figure 1. Flowchart of the subjects included in the study.
FMS testing procedure=Functional Movement Screen testing procedure;
non-MS injury= nonmusculoskeletal injury;
non–PA-related injury=nonphysical activity–related injuries.

2.3. Procedures

Functional Movement Screen and Pain Screening. The FMS is a screening instrument designed for the evaluation of mobility and stability (12,13). The FMS includes 7 tests: the deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability. The FMS was performed by 10 novice trained raters using a standardized procedure. Although it has been previously shown that only 2-hour education on using FMS as a diagnostic tool is sufficient to reach acceptable inter-rater and intrarater reliability (57), raters underwent 2-day education and training procedures by a FMS-certified practitioner. In addition to this, 2 familiarization sessions were conducted to optimize the consistency and accuracy of raters. Each subject had a maximum of 3 trials for each test in accordance with the recommended protocol (12,13). Each test was scored on a 3-point scale, from 0 to 3, with higher scores indicating better functional movement. It has been shown that pain can alter movement control (58). Therefore, subjects were asked if they felt pain during the FMS testing procedure and were subsequently excluded if answered positively to the question (n=53). For each test, the highest score from the 3 trials was recorded. An overall composite score was calculated by summing 7 individual tests with a total FMS score of 21 according to standardized guidelines (12,13).

Body Mass Index and Body Fat Percentage. Body mass was measured with a standard scale to the nearest 0.1 kg. Height was taken to the nearest 0.1 cm using an anthropometer (GPM, Siber-Hegner & Co., Zurich, Switzerland). After this, the BMI was calculated as body mass in kilograms divided by body height in meters squared (kg/m^2) (27). The sum of 4 skinfolds was used as an indicator of body fat content. Skinfold measurements were taken on the right side of the body at the following sites to the nearest 0.2 mm using the Harpenden skinfold caliper (British indicators, West Sussex, United Kingdom): (a) triceps—at the back of the upper arm, halfway between the acromion process and the olecranon process, (b) subscapular—about 2 cm below the lower angle of the scapula; a diagonal fold. The percentage of body fat was calculated using the equation proposed by Slauther et al. (56). All skinfold measures were taken by a skilled technician in triplicate, and median values were retained for analyses.

Physical Activity Assessment, Sports Participation Assessment, and Socioeconomic Status. Physical activity was assessed with a computerized version of the School Health Action, Planning, and Evaluation System (SHAPES) questionnaire (71). The average daily time spent performing MVPA was calculated by summing the weekly time spent performing VPA and MPA divided by 7. As for the validity of this instrument, the same study found that MVPA estimated using the SHAPES questionnaire correlated moderately with the accelerometer-derived value (r=0.44). These results are comparable with other PA questionnaires for youth because the reliability study of the SHAPES questionnaire exhibited moderate agreement for moderate and vigorous PA (71). The original SHAPES questionnaire was supplemented with 2 YES/NO questions inquiring about regular participation in organized sports in school and outside of the school. Because subjects identified all the sports in which they participated regularly, those who stated that they participated in organized sports were offered an extensive list of sports activities. Finally, a question about the weekly duration of sports activities and training (in 1-hour increments) was also included. The socioeconomic status was assessed by an 1-item question: "how would you rate your socioeconomic status?". Responses were arranged on an ordinal scale as follows: 1—much lower than average, 2—lower than average, 3—average, 4—higher than average, and 5—much higher than average.

Assessment of Injury Occurrence. Data on injury occurrence were collected with a computerized self-reported questionnaire 1 year after FMS testing. A recent review shows that an updated *The Oslo Sports Trauma Research Centre overuse injury questionnaire* has potential for wide clinical usage (8). Therefore, we developed a questionnaire with similar core concepts. While completing the questionnaire, subjects were staying at their resident school, 1 or 2 raters (kinesiology graduates) were on disposition to assist with any possible doubts about injury definition or reporting. Subjects were required to answer whether or not they sustained an injury (yes/no answer) over a 1-year period. Also, they were required to report all injuries that occurred over a 1-year period. The severity of the injury was defined as one which precluded participation in PA for at least 1 week (63). Also, this definition was taken because of recall bias issue, where possibility to recall injury that lasted longer than a few days is higher than recalling 1-day injury. The importance of this kind of definition that is related to the health status and PA is well discussed and supported in the research work performed by van Mechelen (66) who points out that “definition of injury should be based on a concept of health other than that customary in standard medicine.” Also, our definition is similar to the definition of National Athletic Injury Registration System in the United States., where the main criteria for injury to be established is the length of incapacitation/absence of PA expressed in a number of days (time loss injury) (2). Overuse injuries as well as acute and subacute injuries were included in the analysis. Therefore, the explicit definition of an injury in this research was defined as: “PA-related musculoskeletal injury which included minor to severe injuries that happened in the past 1-year period.” In addition, Gabbe et al. reported the perfect agreement (k=1.00, 95% confidence interval [CI] 1.00–1.00) between retrospective and prospective records when subjects were asked whether or not an injury had occurred during the 1-year period (yes/no answer) (26). Questionnaire used in this study provided information about the nature of injuries such as the number of injuries, injured body region, and about the context of an injury (during an activity or not and during which activity injuries occurred). Although recall accuracy decreases as the number of detail increases, the validity of self-reported injury (with yes/no answer) in the 12-month period has shown to be perfect (26).

2.4. Statistical Analysis

To identify the optimal cut-point of the total FMS score for predicting injury, receiver operating characteristic (ROC) curve was calculated. The optimal point on the curve was realized when the true-positive rate (sensitivity) was maximized and the false-positive rate (1-specificity) minimized, identifying the point with the highest Youden Index (J). Moreover, the area under the curve (AUC) along with the odds ratio (OR) (95% CI) were calculated with simple logistic regression analysis. To account for the risk related to competitive and noncompetitive sports, all analysis were repeated in the groups of children who participated or did not participate, in organized sports. There were no missing data in any analysis. Data are presented as mean values ± SD. The statistical analyses were performed by using statistical package MedCalc (version 19.1.5.), and the level of the statistical significance was set at $p \leq 0.05$.

2.5. Machine Learning

Because ML has shown good predictive value in the medical field (37,53), similar concepts are applied in this study. In contrast to traditional statistical methods, ML methods aim to estimate the predictive power within the data by maximizing prediction accuracy, often at the expense of interpretability. Machine learning analyses were conducted separately for the groups of children who participate and who do not participate in organized sports. In this study, the ML 3-step approach for cross-validation and selection of the methods is demonstrated in Figure 2. In addition, the authors of this article followed the TRIPOD reporting guidelines for diagnostic and prognostic studies (11). All ML-related analyses were conducted using MATLAB version 9.6.

2.5.1. Input Features and Outcome

Based on the current literature, we selected features that are related to injury occurrence (5,21,32). For nonathletic subjects, we selected the variables that are measured at baseline: sex, age, socioeconomic status, body fat, MVPA, and total FMS score. The same variables were measured in athletic subjects along with training hours per week because the nonathletic population does not participate in sports competitions or training. Thus, for athletic subjects, we selected the above-mentioned variables and training hours per week. A binary outcome measure of injury (yes/ no) was used.

2.5.2. Cross-Validation and Classification Algorithms

To avoid overfitting, and to estimate the generalizability of our ML-based injury prediction results, we used cross-validation. Specifically, all analyses were conducted in a repeated nested 20-fold cross-validated manner. Subjects are randomly assigned to 20 “folds.” In each iteration, the classifier’s hyperparameters are optimized by maximizing the nested 19fold classification accuracy, and the classifier is finally trained on the same 19 “folds,” using the optimal hyperparameters. The remaining fold is used for independent testing of the classifier’s performance. Repeating the described procedure iteratively results in each of the 20 data “folds” being used once as the test set. Varma et al. (65) in their work evaluated validity of different cross-validation strategies, and found that using such nested cross-validation procedure, provides an almost unbiased estimate of the true error, that is very close to that which would be obtained on an independent testing set. Therefore, the described procedure provides a reliable estimate of the classifiers prediction performance on unseen data. Because the current study deals with a binary classification problem, we compare the performance of 4 commonly used out-of-the-box classification algorithms: (a) linear regression—optimized hyperparameters were regularization term strength (l) and type of learner, (b) linear discriminant—optimized hyperparameters were the linear coefficient threshold and amount of regularization, (c) Naïve Bayes—optimized hyperparameters were distribution type and kernel smoothing window width, and (d) k-nearest neighbors—optimized hyperparameters were number of neighbors and distance metric. At each iteration of the described nested 20-fold cross-validation loop, the model specific hyperparameters were optimized using Bayesian optimization with 100 objective evaluations. The described cross-validation procedure was repeated 20 times to reduce the random splitting variance, and the mean performance metrics are reported for each classifier.

2.5.3. Selection of the Model Based on Accuracy Metrics

We selected a model with the highest value of the mean area under the ROC curve (AUC) as an estimate of the best predictive accuracy. It has been shown that AUC can be used as an accuracy metric for the evaluation of different ML algorithms (7). The receiver operating characteristic curve was plotted, and the mean AUC calculated along with mean values of sensitivity, specificity, and OR (95% CI) for each model. According to the literature (22,30), AUC of 0.50–0.60 demonstrates prediction at chance, 0.60–0.70 poor prediction, 0.70–0.80 fair prediction, 0.80–0.90 good prediction, and 0.90–1.0 excellent prediction.

2.5.4. Feature Importance

To assess importance of specific features, the least absolute shrinkage and selection operator (LASSO) method was conducted post-hoc, in both the nonathletic and athletic group of subjects. Least absolute shrinkage and selection operator is a linear regression–based method, where models are trained for increasing values of the regularization term strength (λ) values, thus forcing to model coefficients to gradually shrink in size. Eventually, as l is increased, more coefficients will be forced to be 0, eliminating the corresponding features from the model and leaving only the most important ones (23).

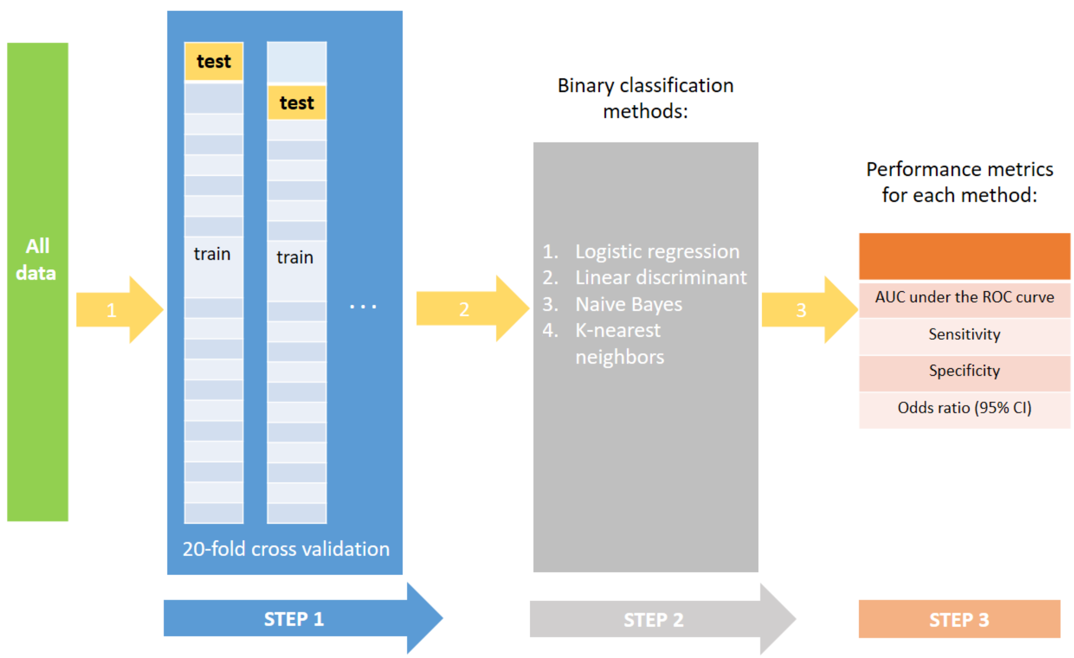


Figure 2. Machine learning 3-step approach for cross-validation and selection of the methods

3. Results

3.1. Results of Statistical Analysis

Table 1 presents basic characteristics of subjects at baseline stratified by gender. Table 2 presents basic epidemiological data for injured subjects among the athletic and nonathletic population 1 year after baseline measurements.

Table 1. Basic descriptive characteristics for participants by gender at baseline.

	N	Age mean± SD	% Body Fat mean ±SD	BMI mean ±SD	MVPA (min/day) mean± SD	Sport participation N (%)		SES median
						Yes	No	
Girls	279	16.6 ±0.4	23.8 ± 4.2	21,6 ±3,2	103,5 ±71.1	63 (23)	216 (77)	3
Boys	277	16.6 ± 0.4	18.2 ± 6.7	22.3± 3.5	136.0 ±83.2	129 (47)	148 (53)	3

% Body Fat - Percentage of Body Fat; BMI - Body mass index, MVPA - Moderate-to-vigorous Physical Activity; SES - socioeconomic status (1- Much lower than average, 2- Lower than average, 3- Average, 4- Higher than average, 5- Much higher than average).

The total FMS score was higher in girls compared with boys (t-value: 2.88, p = 0.006) (12.8 vs. 12.2). The T-test did not show a significant difference between injured and uninjured in the total FMS score, regarding neither nonathletic (12.8 vs. 12.4; t-value: 20.92, p 5 0.35) nor athletic subjects (12.9 vs. 12.5; t-value: 21.22, p 5 0.22). Results of the ROC curve analysis including the FMS total score as a single predictor and injury as a binary outcome for the nonathletic population showed AUC of 0.54 (95% CI: 0.48–0.59) and Youden Index of 0.12 with associated criterium of the total FMS score >12 (sensitivity: 61% and specificity: 51%). Simple logistic regression did not reveal significant associations, although a trend that higher FMS score increased the odds for injury was evident (OR: 1.06; 95% CI: 0.93–1.22). On the other hand, results of ROC curve analysis for the athletic population showed the AUC of 0.56 (95% CI:

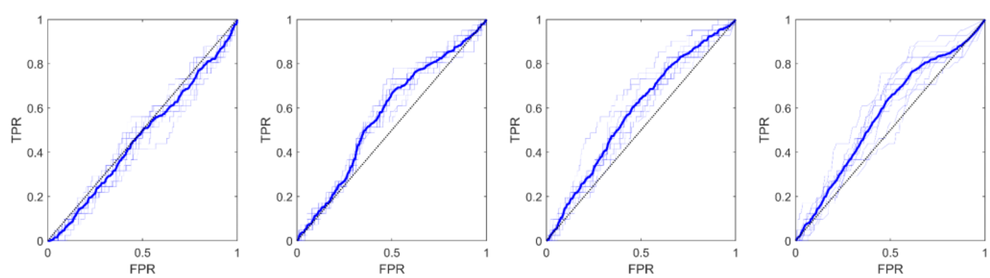
0.47–0.63) and Youden Index of 0.15 with associated FMS total score criterium >12 (sensitivity: 60%; specificity: 54%). Logistic regression for predicting injury occurrence with a single predictor (total FMS score) did not show statistical significance but revealed that OR was 1.09 (95% CI: 0.95–1.26) and reversely related to total FMS scores.

Table 2. Basic epidemiological data for injured subjects among the athletic and non-athletic populations.

	General information about injured subjects				**Number of injured subjects according to location**							
	Total number of injured participants	**Median number of injuries (25th percentile-75th percentile)**	**Sex N**		**Lower extremities**				**Upper extremities**		**Trunk**	**Other**
			girls	**boys**	**foot**	**ankle**	**knee**	**hip**	**hand**	**should-er**		
Non athletic	41	3 (2-5)	17	24	17	21	19	2	17	8	10	18
Athletic	49	3 (2-6)	12	37	11	23	28	5	18	11	17	23

Results of the Machine Learning

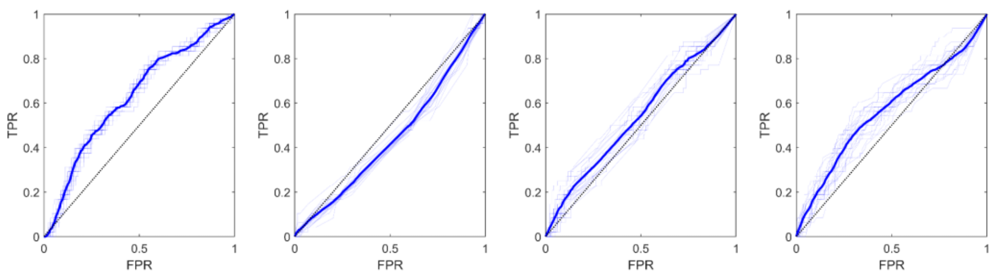
Results of ML ROC plots and tables with associated prediction performance metrics for each method are shown in Figures 3 and 4, for nonathletic and athletic subjects, respectively. Among the nonathletic subjects, Naïve Bayes showed the highest value of AUC (0.58) and was therefore selected as the model with the highest predictive accuracy for injury incidence. However, linear discriminant showed highest values of sensitivity (0.71) and OR (95% CI) (2.30, 1.97–2.70), whereas the highest value of specificity was demonstrated by the linear regression (0.55) (Figure 3.). Within athletic subjects, linear regression showed the highest value of AUC (0.62), sensitivity (0.59), and OR (95% CI) (2.66, 2.29–3.09) and, thus, was chosen as the model with the highest predictive accuracy. On the other hand, Naïve Bayes demonstrated the highest value for specificity (0.71) (Figure 4.).



	Logistic regression	Linear discriminant	Naïve Bayes	kNN
AUC	0.47	0.57	**0.58**	0.57
Sens	0.50	**0.71**	0.70	0.69
Spec	**0.55**	0.49	0.49	0.50
OR (95%CI)	1.24 (1.07 - 1.44)	**2.30 (1.97 – 2.70)**	2.29 (1.96 – 2.68)	2.25 (1.93 – 2.63)

Figure 3. Receiver operating characteristic (ROC) plots and table with associated accuracy metrics for each method among nonathletic subjects. TPR = true positive rate; FPR = false positive rate; kNN = k-nearest neighbors; AUC = area under the curve; Sens = sensitivity; Spec = specificity; OR (95%) = odds ratio with 95% confidence intervals.

Results of the LASSO method revealed that among all features in nonathletic youth, sex contributed most to the injury prediction model; specifically, results suggest that boys are more prone to higher injury incidence (positive coefficient β). Body fat, socioeconomic status, and total FMS score seems to contribute to the model as well, but in a lesser degree compared with sex (for body fat demonstrated negative β coefficient, whereas β coefficients for socioeconomic status and total FMS score were positive). On the other hand, MVPA (negative β coefficient) and age (positive β coefficient) did not enhance the model excessively (Figure 5). Among athletic subjects, coefficient associated with training hours per week remained positive for large values of λ. However, most of the remained coefficients were shrinked to 0 (Figure 5.).



	Logistic regression	Linear discriminant	Naïve Bayes	kNN
AUC	**0.62**	0.44	0.54	0.57
Sens	**0.59**	0.43	0.41	0.53
Spec	0.65	0.60	**0.71**	0.66
OR (95%CI)	**2.66 (2.29 – 3.09)**	1.10 (0.95 – 1.27)	1.67 (1.43 – 1.94)	2.20 (1.90 – 2.55)

Figure 4. Receiver operating characteristic (ROC) plots and table with associated accuracy metrics for each method among athletic subjects. TPR = true positive rate; FPR 5 false positive rate; kNN = k-nearest neighbors; AUC = area under the curve; Sens = sensitivity; Spec = specificity; OR (95%) = odds ratio with 95% confidence intervals.

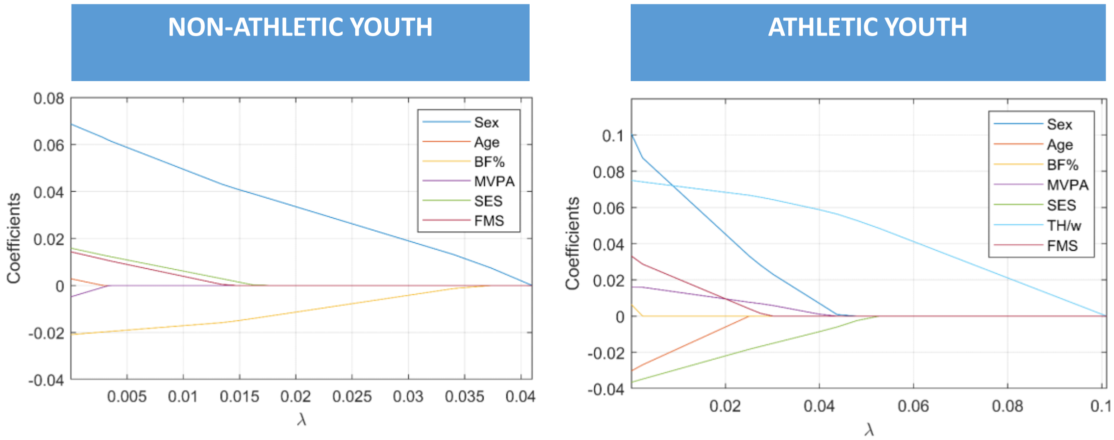


Figure 5. Results of the LASSO method for nonathletic and athletic youth. λ= regularization term strength value; BF% = percentage (%) of body fat; MVPA = moderate-to-vigorous physical activity; SES = socioeconomic status; FMS = total Functional Movement Screen score; TH/w = training hours per week; LASSO = least absolute shrinkage and selection operator.

4. Discussion

This is the first study that has investigated injury prediction by FMS in the average adolescent population. Our results strongly suggest that FMS was unable to predict injury in the average adolescent population. Furthermore, total FMS cut-off scores did not successfully discriminate between injured and uninjured subjects, neither in nonathletic (AUC: 0.54, 95% CI: 0.48–0.59) nor in athletic youth (AUC: 0.56, 95% CI: 0.47–0.63). The results of our study are hardly surprising because in the past few years several articles (43,46,48,68) have seriously undermined the predictive validity of the FMS among various populations (adults, athletes, firefighters, etc.). Emphasizing that although reliability of the test is excellent (68), it is not enough as FMS does not demonstrate the properties essential to be considered as a measurement scale and has neither measurement nor predictive validity (46). What our study adds to this is that the same is also true for studies on adolescents, regardless of their training status. Previous studies investigating association between FMS and injury occurrence have covered mainly the athletic adolescent population. For example, a study that included 119 male and female college basketball players who performed FMS preseason and postseason did not show significant discriminatory power of FMS to predict injury occurrence and have reported AUC of 0.43–0.49 (4). Furthermore, in a study where 27 injury-free adolescent cricket players were prospectively followed over a season, after performing a preseason FMS screening, the authors concluded that the composite FMS score is a poor predictor of in-season injury (39). Finally, in 167 high-school athletes who were monitored for injury during a single season only, in-line lunge scores were significantly higher for injured players, suggesting that FMS should not be used of overall injury predictions in high-school athletes. Our results are further expanding such conclusions to PA-related injuries in nontrained adolescents.

The reason for such poor discriminating ability of FMS is probably questionable relationship between injury risk factors and components of FMS (10). Indeed, established modifiable risk factors for common injuries include physical fitness components such as muscle strength (15) and single-leg balance (16), or neuromuscular control in high-risk movements such as jump-landing (44) or sprinting (54). Movement patterns that comprise FMS do not have high requirements for these physical fitness qualities nor do they include high-risk sporting actions.

Hence, it is not surprising that injury prediction may be poor in such cases because what we measure with FMS is not reflected on any risk factor. Furthermore, injury is a multifactorial event and expecting that only movement quality will be enough to explain the whole variance of injury occurrence is wrong in the beginning (3). In that regard, Bahr emphasized that, to this date, there is no intervention study that has provided support for injury risk screening. Although some earlier studies showed that the total FMS score below 14 raises the risk of injury among athletes (28,34,35,45,55), over the past years, an increasing number of other studies and meta-analysis have reported the limited value of FMS to predict injury across different populations (6,17,64).

Furthermore, Bahr suggests 3 methodological steps for investigation of injury prediction and prevention (3): (a) strong association between a marker from a screening test and injury risk, (b) test properties have to be investigated in relevant populations with appropriate statistics, and (c) integration of intervention program for athletes with high-injury risk (identified by test screening) have to be more helpful than the same intervention program that was applied to all athletes. Being aware of these issues, the current study incorporated as many suggestions as possible, included a variety of predictive variables, used appropriate statistics, and applied advanced methodology with ML. This methodology and provided conclusions will be discussed in the next section.

The aim of this study was to examine whether FMS alone or in combination with other predictors supported with ML analysis would give a better injury prediction model for a 1-year period among adolescents. Our findings suggest that the ML methodology, validated using a rigorous nested cross-validation procedure, outperformed classical statistical approach in predicting injury through a single predictor—FMS. This can be seen across different performance metrics. The results of this study suggest that the logistic regression gave the best values for most of the metrics for the athletic population, whereas linear discriminant and Naïve Bayes method demonstrated best values for most performance metrics for nonathletic subjects. In addition, among nonathletic subjects, Naïve Bayes showed the highest AUC (0.58), whereas among athletic youth, logistic regression demonstrated the best value of AUC (0.62). Accordingly, aforementioned models were selected as the models with the highest predictive accuracy for injury incidence. This means that with given predictors—sex, age, socioeconomic status, body fat percentage, MVPA, training hours per week (only for athletic subjects), and total FMS score—Naïve Bayes and logistic regression exhibited an overall best prediction performance over other models, for the nonathletic and athletic population, respectively. However, not all predictors have the same influence on the diagnosis of injury incidence. Therefore, we assessed importance of a specific predictor using the LASSO method. In line with this, results of the current study indicate that nonathletic boys who have lower-body fat could be more prone to suffer from injury incidence. Also, findings suggest that boys who participate in sport and spend more time training (in terms of hours spent exercising per week) are at a higher risk of being injured. However, it is difficult to compare our results with findings of other similar studies with application of ML (14,38,51,52,62,72) because of different methodology used. Furthermore, because of the complexity and nonlinearity of the association between injury and predictive factors, the application of ML is strongly encouraged (33).

Authors are aware that etiology of injury is a complex phenomenon which could therefore be studied as a dynamic model (40). Nevertheless, with ML methodology, we offered a novel approach toward injury data analysis. Most studies analyzed in this review (33) did not consider cross-validation, training and testing data set, as well as selecting the right model with best prediction performance. Therefore, they did not comprehensively consider the process of ML, whereas this study included all the mentioned components. Although with ML methodology interpretation is somehow limited, the predictive accuracy of the model, cross-validation, model selection, and determining feature importance can give an additional advantage over the classical statistical approach. Therefore, we encourage researchers to continue using ML within clinical researches related to sport injury prediction. However, instead of using FMS, we recommend that strength and conditioning specialists and physiotherapists use tests that assess established modifiable injury risk factors such as lower-limb muscle strength (15), single-limb balance (16), or neuromuscular control during jump landing (44) or sprinting (54). Such an approach, combined with ML, seems promising in predicting injuries youth soccer (49).

This study has several strengths. First, this is the first study that has investigated the prediction of injury by functional movement quality in a representative sample of urban adolescents. Second, this is the only study that applied ML methodology for the prediction of musculoskeletal injury in the pediatric population. Third, this research is based on a reasonably large number of subjects (n = 556). Finally, this is the only study that has controlled for a large number of predictors (age, sex, sports participation, socioeconomic status, PA level, BMI, and body fat percentage) which should allow more accurate prediction.

However, there are also a few limitations that need to be considered while interpreting these data. This study investigated the population in the urban area, thus excluding children from rural areas which may affect the generalizability of the results in the context of the general adolescent population. Although we included considerable number of predictors, previous injury was not included as the predictor in the models which can influence drawn conclusions about injury prediction. Next, injuries in this study were not assessed prospectively. Although we are aware of potential recall bias of a self-reported injury questionnaire, a previous study has shown a perfect agreement (k = 1.00, 95% CI 1.00–1.00) between a prospective and a retrospective record of reported injury (yes/no answer) during a 1-year period (26). A large number of raters used in this study can be a potential drawback, although good inter-rater agreement in FMS scores has been repeatedly reported (57,61). Because the model obtained with ML is complex and assessment of variables are time consuming, this could present potential limit for the experts and its practical usage. Despite all this, the results of this study give valuable information on injury prediction among the pediatric population.

Future research should focus on the investigation of the influence of different predictors of injury in the adolescent population. Also, we strongly encourage the application of ML methodology and rigorous cross-validation procedures for future researchers which will yield a more accurate prediction that, in turn, could be better transferred into clinical practice.

Practical Applications

Our results do not support the use of FMS screening in injury prediction in the athletic and nonathletic population of adolescents. In addition, total FMS cut-off scores for athletic and nonathletic subjects did not successfully discriminate those who suffered from those who did not suffer from injury. The total FMS cut-off score does not discriminate between subjects with and without injury regardless of participation in organized sports training (e.g., athletic vs. nonathletic).

However, ML outperformed traditional methods and showed that within the athletic and nonathletic subgroup, ML exhibited better performance of the metrics overall. This means that with given predictors—sex, age, BMI, body fat percentage, MVPA, training hours per week, socioeconomic status, and functional movement—our ML model can give a more accurate prediction. Furthermore, nonathletic boys who have lower-body fat could be more prone to suffer from injury incidence. Also, findings suggest that boys who participate in sport and spend more time training are at a higher risk of being injured. This information could help practitioners in identifying the risk group of adolescents that could be more prone to injuries in the future. Clinicians need to be cautious while implementing FMS into practice among the average adolescent population. Functional movement screen cut-off point frequently proposed by the literature does not discriminate those who are likely to sustain an injury from those who will not get injured. Therefore, the FMS cut-off point reported in this and previous studies should not be incorporated in clinical practice among the adolescent population. Although our research does not support FMS as an injury prediction tool, we believe that FMS should be used for the following: movement quality assessment, revealing movement asymmetry, as a starting point for the progression of future exercise, and for pain screening during basic movement patterns.

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References

1. Abassi M, Bleakley C, Whiteley R. Athletes at late stage rehabilitation have persisting deficits in plantar- and dorsiflexion, and inversion (but not eversion) after ankle sprain. *Phys Ther Sport* 38: 30–35, 2019.

2. Alles WF, Powell JW, Buckley W, et al. The National Athletic Injury/ Illness Reporting System 3-year findings of high school and college football injuries. *J Orthop Sports Phys Ther* 1: 103–108, 1979.

3. Bahr R. Why screening tests to predict injury do not work-and probably never will…: A critical review. Br J Sports Med 50: 776–780, 2016.

4. Bond CW, Dorman JC, Odney TO, et al. Evaluation of the functional movement screen and a novel basketball mobility test as an injury prediction tool for collegiate basketball players. *J Strength Cond Res* 33: 1589–1600, 2019.

5. Bloemers F, Collard D, Paw MCA, et al. Physical inactivity is a risk factor for physical activity-related injuries in children. Br J Sports Med 46: 669–674, 2012.

6. Bunn P dos S, Rodrigues AI, Bezerra da Silva E. The association between the functional movement screen outcome and the incidence of musculoskeletal injuries: A systematic review with meta-analysis. *Phys Ther Sport* 35: 146–158, 2019.

7. Bradley AP. The use of the area under the ROC curve in the evaluation of machine learning algorithms. *Pattern Recognit* 30: 1145–1159, 1997.

8. Clarsen B, Bahr R, Myklebust G, et al. Improved reporting of overuse injuries and health problems in sport: An update of the Oslo sport trauma research center questionnaires. *Br J Sports Med* 0: 1–7, 2020.

9. Claudino JG, Capanema D de O, de Souza TV, et al. Current approaches to the use of artificial intelligence for injury risk assessment and performance prediction in team sports: A systematic review. *Sport Med Open* 5: 1–12, 2019.

10. Clifton DR, Harrison BC, Hertel J, et al. Relationship between functional assessments and exercise-related changes during static balance. *J Strength Cond Res* 27: 966–972, 2013.

11. Collins GS, Reitsma JB, Altman DG, et al. G. Transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD): The TRIPOD statement. *BMJ* 350: 1–9, 2015.

12. Cook G, Burton L, Hoogenboom B. Pre-participation screening: The use of fundamental movements as an assessment of function–Part 2. *North Am J Sport Phys Ther* 1: 62–72, 2006.

13. Cook G, Burton L. Pre-participation screening the use of fundamental movements as an assessment of function Part 1. *North Am J Sport Phys Ther* 1: 62–72, 2016.

14. Connaboy C, Eagle SR, Johnson CD, et al. Using machine learning to predict lower-extremity injury in US special forces. *Med Sci Sports Exerc* 51: 1073–1079, 2019.

15. de la Motte SJ, Gribbin TC, Lisman P, et al. Systematic review of the association between physical fitness and musculoskeletal injury risk: Part 2-muscular endurance and muscular strength. *J Strength Cond Res* 31: 3218–3234, 2017.

16. de la Motte SJ, Lisman P, Gribbin TC, et al. Systematic review of the association between physical fitness and musculoskeletal injury risk: Part 3-flexibility, power, speed, balance, and agility. *J Strength Cond Res* 33: 1723–1735, 2019.

17. Dorrel BS, Long T, Shaffer S, et al. Evaluation of the functional movement screen as an injury prediction tool among active adult populations: A systematic review and meta-analysis. *Sports Health* 7: 532–537, 2015.

18. Dowd MD, Keenan HT, Bratton SL. Epidemiology and prevention of childhood injuries. *Crit Care Med* 30: 385–392, 2002.

19. Emery CA. Risk factors for injury in child and adolescent sport: A systematic review of the literature. *Br J Sports Med* 49: 1094–1099, 2015.

20. Emery CA, Hagel B, Morrongiello BA. Injury prevention in child and adolescent Sport: Whose responsibility is it ?. *Clin J Sport Med* 16: 514–521, 2006.

21. Emery CA, Tyreman H. Sport participation, sport injury, risk factors and sport safety practices in Calgary and area junior high schools. *Paediatr Child Health (Oxford)* 14: 439–444, 2009.

22. Fawcett T. ROC graphs: Notes and practical considerations for researchers. *Mach Learn* 31: 1–38, 2004.

23. Fonti V, Belitser E. Feature selection using lasso. *VU Amsterdam Res Paper Business Analytics* 30: 1–25, 2017.

24. Friden T, Roberts D, Zatterstrom R, et al. Proprioception after an acute knee ligament injury: A longitudinal study on 16 consecutive patients. *J Orthop Res* 15: 637–644, 1997.

25. Friel K, McLean N, Myers C, et al. Ipsilateral hip abductor weakness after inversion ankle sprain. *J Athl Train* 41: 74–78, 2006.

26. Gabbe BJ, Finch CF, Bennell KL, et al. How valid is a self reported 12 month sports injury history?. *Br J Sports Med* 37: 545–547, 2003.

27. Garrow JS, Webster J. Quetelet's index (W/H2) as a measure of fatness. *Int J Obes* 9: 147–153, 1985.

28. Garrison M, Westrick R, Johnson MR, et al. Association between the functional movement screen and injury development in college athletes. *Int J Sports Phys Ther* 10: 21–28, 2015.

29. Gribble PA, Bleakley CM, Caulfield BM, et al. Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *Br J Sports Med* 50: 1496–1505, 2016.

30. Harrell FE Jr, Lee KL, Mark DB. Tutorial in biostatistics. Multivariable prognostic models: Issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors. *Stat Med* 15: 361–387, 1996.

31. Hertel J, Buckley WE, Denegar CR. Serial testing of postural control after acute lateral ankle sprain. *J Athl Train* 36: 363–368, 2001.

32. Jespersen E, Verhagen E, Holst R, et al. Total body fat percentage and body mass index and the association with lower extremity injuries in children: A 2.5-year longitudinal study. *Br J Sports Med* 48: 1497–1501, 2014.

33. Kakavas G, Malliaropoulos N, Pruna R, et al. Artificial intelligence. A tool for sports trauma prediction. *Injury* 0: 8–10, 2019.

34. Kiesel KB, Butler RJ, Plisky PJ. Prediction of injury by limited and asymmetrical fundamental movement patterns in American football players. *J Sport Rehabil* 23: 88–94, 2014.

35. Kiesel K, Plisky PJ, Voight ML. Can serious injury in professional football be predicted by a preseason functional movement screen? *N Am J Sports Phys Ther* 2: 147–158, 2007.

36. Kollock RO, Lyons M, Sanders G, et al. The effectiveness of the functional movement screen in determining injury risk in tactical occupations. *Ind Health* 57: 406–418, 2019.

37. Liu NT, Salinas J. Machine learning for predicting outcomes in trauma. *Shock* 48: 504–510, 2017.

38. Lopez-Valenciano A, Ayala F, Puerta JM, et al. A preventive model for muscle injuries: A novel approach based on learning algorithms. *Med Sci Sports Exerc* 50: 915–927, 2018.

39. Martin C, Olivier B, Benjamin N. The functional movement screen in the prediction of injury in adolescent cricket pace bowlers: An observational study. *J Sport Rehabil* 26: 386–395, 2017.

40. Meeuwisse WH, Tyreman H, Hagel B, et al. A dynamic model of etiology in sport Injury: The recursive nature of risk and causation. *Clin J Sport Med* 17: 215 219, 2007.

41. Mjolsness E, DeCoste D. Machine learning for science: State of the art and future prospects. *Scienc*e 293: 2051–2055, 2001.

42. Mock C, Cherian MN. The global burden of musculoskeletal injuries: Challenges and solutions. *Clin OrthopRelat Res* 466: 2306–23016, 2008.

43. Moran RW, Schneiders AG, Mason J, et al. Do functional movement screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis. *Br J Sports Med* 51: 1661–1669, 2017.

44. Padua DA, Marshall SW, Boling MC, et al. The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med* 37: 1996–2002, 2009.

45. Pfeifer CE, Sacko RS, Ortaglia A, et al. Functional movement screen in youth sport participants: Evaluating the proficiency barrier for injury. *Int J Sports Phys* Ther 14: 436–444, 2019.

46. Philp F, Blana D, Chadwick EK, et al. Study of the measurement and predictive validity of the functional movement screen. *BMJ Open Sport Exerc Med* 4: 1–7, 2018.

47. Pickett W, Schmid H, Boyce WF, et al. Multiple risk behavior and injury. *Arch Pediatr Adolesc Med* 156: 786–793, 2002.

48. Pollen TR, Keitt F, Trojian TH. Do normative composite scores on the functional movement screen differ across high school, collegiate, and professional athletes? A critical review. *Clin J Sport Med* 00: 1–12, 2018.

49. Rommers N, Rössler R, Verhagen E, et al. A machine learning approach to assess injury risk in elite youth football players. *Med Sci Sports Exerc* 52: 1745–1751, 2020.

50. Rosenfeld SB, Schroeder K, Watkins-Castillo SI. The economic burden of musculoskeletal disease in children and adolescents in the United States. *J Pediatr Orthop* 38: 230–236, 2018.

51. Rossi A, Pappalardo L, Cintia P, et al. Effective injury forecasting in soccer with GPS training data and machine learning. *PLoS One* 13: 1–15, 2018.

52. Ruddy JD, Shield AJ, Maniar N, et al. Predictive modeling of hamstring strain injuries in elite Australian footballers. *Med Sci Sport Exerc* 50: 906–914, 2018.

53. Saria S, Butte A, Sheikh A. Better medicine through machine learning: What's real, and what's artificial?. *Plos Med* 15: 1–5, 2018.

54. Schuermans J, Danneels L, Van Tiggelen D, et al. Proximal neuromuscular control protects against hamstring injuries in male soccer players: A prospective study with electromyography time-series analysis during maximal sprinting. *Am J Sports Med* 45: 1315–1325, 2017.

55. Shojaedin SS, Letafatkar A, Hadadnezhad M, et al. Relationship between functional movement screening score and history of injury and identifying the predictive value of the FMS for injury. *Int J Inj Contr Saf Promot* 21: 355–360, 2014.

56. Slaughter AMH, Lohman TG, Boileau RA, et al. Skinfold equations for estimation of body fatness in children and youth. *Hum Biol* 60: 709–723, 1988.

57. Smith CA, Chimera NJ, Wright NJ, et al. Interrater and intrarater reliability of the functional movement screen. *J Strength Cond Res* 24: 83–87, 2009.

58. Sterling M, Jull G, Wright A. The effect of musculoskeletal pain on motor activity and control. *J Pain* 2: 135–145, 2001.

59. Storm JM, Wolman R, Bakker EWP, et al. The relationship between range of motion and injuries in adolescent dancers and sportspersons: A systematic review. *Front Psychol* 9: 1–14, 2018.

60. Štefan L, Mišigoj-Duraković M, Devrnja A, et al. Tracking of physical activity, sport participation, and sedentary behaviors over four years of high school. *Sustain* 10: 1–13, 2018.

61. Teyhen DS, Shaffer SW, Lorenson CL, et al. The functional movement screen: A reliability study. *J Orthop Sport Phys Ther* 42: 530–540, 2012.

62. Thornton HR, Delaney JA, Duthie GM, et al. Importance of various training load measures on injury incidence of professional rugby league athletes. *Int J Sports Physiol Perform* 12: 819–824, 2017.

63. Timpka T, Alonso J, Jacobsson J, et al. Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics track and field): Consensus statement. *Br J Sports Med* 48: 483–490,
2014.

64. Trinidad-Fernandez M, Gonzalez-Sanchez M, Cuesta-Vargas AI. Is a low functional movement screen score (#14/21) associated with injuries in sport? A systematic review and meta-analysis. *BMJ Open Sport Exerc Med* 5: 1–10, 2019.

65. Varma S, Simon R. Bias in error estimation when using cross-validation for model selection. *BMC Bioinformatics* 7: 1–8, 2006.

66. van Mechelen W, Hlobil H, Kemper HCG. Incidence, severity, aetiology and prevention of sports injuries. *Sport Med* 14: 82–99, 1992.

67. Walsh SS, Jarvis SN. Measuring the frequency of “severe” accidental injury in childhood. *J Epidemiol Community Health* 46: 26–32, 1992.

68. Warren M, Lininger M, Chimera N, et al. Utility of FMS to understand injury incidence in sports: Current perspectives. *Open Access J Sport Med* 9: 171–182, 2018.

69. Whittaker J, de la Motte S, Dennett L, et al. Predicting lower extremity injury risk in sport through movement quality screening: A systematic review. *Br J Sport Med* 51: 409–410, 2017.

70. Williams JM, Currie CE, Wright P, et al. Socioeconomic status and adolescent injuries. *Soc Sci Med* 44: 1881–1891, 1996.

71. Wong SL, Leatherdale ST, Manske S. Reliability and validity of a school-based physical activity questionnaire. *Med Sci Sports Exerc* 38: 1593–1600, 2006.

72. Zelič I., Kononenko I, Lavrač N, et al. Induction of decision trees and bayesian classification applied to diagnosis of sport injuries. *J Med Syst* 21: 429–444, 1997.

GENERAL CONCLUSION

To this date, there are no studies that have investigated the relationship between various parameters of PA and adiposity and functional movement in the mid adolescent population. Also, there was a lack of studies investigating the prediction of injuries via FMS^{TM} using ML in the mid-adolescent population. This doctoral thesis provided three new and important scientific insights. Findings of this doctoral thesis suggest that movement quality is positively associated with PA level and negatively associated with adiposity in the adolescent population. Additionally, results demonstrated that exhibition of better movement quality does not 'protect' average adolescent from being injured.

More specifically, the findings of this thesis indicate that level of PA is positively associated with functional movement in adolescent girls, but not in boys, where the type of PA moderates these associations. There could be two main potentially overlapping relationships behind the observed relationship between PA and functional movement: *1) Neuromuscular relationship:* A higher PA level is usually related to better motor coordination and motor proficiency (Wrotniak et al., 2006), and postural control (Baghbani et al., 2016), which can, in turn, be related to a better quality of movement patterns. At the same time, evidence suggests that a lower level of PA is related to suboptimal proprioception (Ribeiro & Oliveir, 2011) and may limit motor control leading to dysfunctional movement patterns; *2) Psychomotor relationship:* Children who are more engaged in PA and sports activities have a wider variety of movement patterns. Through sports activities and practices, children are engaged in the motor learning process where they learning different movement patterns. It has been shown how multiple motor learning experiences can enhance motor adaptability (Seidler, 2004). This could have a positive effect on movement quality. However, our findings suggest that the psychomotor and neuromuscular relationship between movement patterns and type of PA can be specific. According to the results of our study, it seems that engaging in different types of sports activities has a different effect on movement quality. More specifically, in girls, participation in dance improved functional movement significantly, while there might be also a positive relationship between volleyball and movement quality. Conversely, the results of this study indicate that participation in football is negatively related to movement quality among boys. Although this relationship did not reach statistical significance, it is important to note that previous studies have shown that football players are exhibiting progressive limitation in flexibility and joint mobility through adolescence (Cejudo et al., 2019) and have a greater risk for degenerative hip joint problems already at the early age of adolescence (de Silva et al., 2016).

There is an obvious sex difference in the relation between different types of PA and functional movement. In this study, girls are in the last stage of maturation, while boys are not, which could potentially influence the quality of movement among both sexes. Because girls are more engaged in aesthetic sports activities, which improve functional movement, and unlike boys are in the last stage of maturation, these factors combined could affect sexual dimorphism in the quality of movement among the adolescent population. This can also explain the difference between boys and girls related to the association between type of PA and functional movement. However, more studies are needed in order to examine the effect of maturation on functional movement and different types of PA in the adolescent population. These findings underline the importance of developing functional movement during childhood and adolescence. Providing children and youth with the opportunity to develop functional movement should be considered a key antecedent in enabling children to lead physically active lives. In other words, intensive PA does not guarantee optimal movement quality since engaging in some type of sport activities, especially when exercise intensity is higher than a person's physical fitness level, can result in dysfunctional movement patterns.

Besides the positive effect of PA level on movement quality, it seems that there is an inverse relationship between movement quality and adiposity in adolescent population. Current thesis presents novel data demonstrating that overweight and obesity could possibly have a detrimental effect on movement quality, as assessed by the FMS^{TM}, in boys, but not girls. Of particular note, although FMS scores were poorer in boys with overweight compared to boys with normal weight, being overweight and obese did not appear to confer the same detriment on quality of movement in girls. This means that the association between adiposity and FM in adolescence is sex-specific, suggesting that boys with overweight and obesity could be more prone to develop dysfunctional movement patterns. There are two possible explanations behind the observed sex-specific relationship between adiposity and movement quality in mid-adolescents. *1) Neuromechanical:* Evidence shows that adolescent boys are more prone to develop postural misalignment, such as hyperkyphosis compared to girls (Dolphens et al., 2013; Jankowicz-Szymańska et al., 2019); since kyphotic posture decreases concentric activity of the thoracic paraspinal muscles, this could directly limit shoulder mobility test whereas this movement pattern requires active thoracic extension (i.e., demands concentric action of the paraspinal thoracic extensors muscles) (Cook et al., 2006a; Cook & Burton, 2016; Gray Cook, 2011). Moreover, hyperkyphosis can directly limit the optimal performance of the squat, inline lunge, and rotary stability since these patterns demand maintaining neutral spine position and co-contraction of the paraspinal thoracic muscles (Cook et al., 2006a; Cook & Burton, 2016; Gray Cook, 2011). Furthermore, flat feet are mostly seen in boys with overweight rather than in girls with overweight (Gijon-Nogueron et al., 2017), which can cause deficits in uni- and contra- lateral lower-extremity stability movement patterns (i.e., in-line lunge and hurdle step) (Cook et al., 2006a; Cook & Burton, 2016; Gray Cook, 2011). Furthermore, adolescent boys with obesity demonstrate impairment of the rectus femoris muscle activation which is recruited while performing lower extremities movement patterns (Blimkie et al., 1990). *2) Physiological:* Sex-specific association between adiposity and movement quality is likely to be the result of the maturation process, which differs between girls and boys and may have different impacts on movement proficiency during childhood and adolescence (Duncan et al., 2017). Looking altogether, deficits which arose from each FMS^{TM} test resulted in a decrease of the total FMS score among boys, but not girls.

Results reported in this thesis do not support the use of FMS screening in injury prediction in an athletic and non-athletic population of adolescents. More precisely, total FMS cut-off scores for athletic and non-athletic participants did not successfully discriminate those who suffered from those who did not suffer from injury. Also, the total FMS cut-off score does not discriminate between participants with and without injury regardless of participation in organized sports training (e.g. athletic vs non-athletic). The reason for such poor discriminating ability of FMS is probably a questionable relationship between injury risk factors and components of FMS (Clifton et al., 2013). Indeed, established modifiable risk factors for common injuries include physical fitness components such as muscle strength (de la Motte et al., 2017) and single-leg balance (de la Motte et al., 2019), or neuromuscular control in high-risk movements such as jump-landing (Padua et al., 2009) or sprinting (Schuermans et al., 2017). Movement patterns that comprise FMS do not have high requirements for these physical fitness qualities nor do they include high-risk sporting actions. Hence, it is not surprising that injury prediction may be poor in such cases because what we measure with FMS is not reflected on any risk factor. Furthermore, injury is a multifactorial event and expecting that only movement quality will be enough to explain the whole variance of injury occurrence is wrong at the beginning (Bahr, 2016). However, ML outperformed traditional methods and showed that within an athletic and non-athletic subgroup, the kNN method exhibited high sensitivity metrics (>0.8). This means that with given predictors: sex, age, BMI, body fat percentage, MVPA, training hours per week, socioeconomic status, and functional movement, our ML model can give a more accurate prediction. More practically, this means that an injury prediction tool with high sensitivity can help rule out the risk of injury in case of a negative output while pointing to further risk mitigation strategies in case of positive output. Clinicians need to be cautious while implementing FMS into practice among the average adolescent population. FMS cut-off point frequently proposed by the literature does not discriminate those who are likely to sustain an injury from those who will not get injured. Therefore, FMS cut-off point reported in this and previous studies should not be incorporated in clinical practice among the adolescent population. Although our research does not support FMS as an injury prediction tool, we believe that FMS should be used for: movement quality assessment; revealing movement asymmetry; as a starting point for the progression of future exercise, and for pain screening during basic movement patterns.

Overall, the results of the current doctoral thesis provide important information on the potential negative impact of adiposity and the positive effect of PA on movement quality in the population of average mid-adolescents. From a practical point of view, our findings could be incorporated into practice as follows: 1) Functional movement patterns should be practiced in an isolated manner, independently of practicing specific sport and other physical activities. In line with this, integration of different injury prevention programs, especially those which facilitate functional movement, such as of ‘11 + Kids’ may be beneficial (Beaudouin et al., 2019) with special emphasis on the boys with overweight and obesity. Therefore, exercise interventions directed toward correcting dysfunctional patterns should be, to some degree, sex-specific. 2) Learning a variety of movement patterns, as well as practicing learned movements and activities at moderate-to-vigorous intensity could be beneficial to potentially reduce the risk of injury incidence, potential orthopaedic abnormalities, and cardiovascular diseases in later life. 3) FMS diagnostic tool should not be considered as an injury prediction tool. However, it can be suggested for assessment of movement quality and movement dysfunctions. This information is particularly important for clinicians, physical therapists, and coaches in youth sport, physical education teachers, and those working in the public health sector.

Strengths and limitations

This doctoral thesis has several strengths. First, this is the first thesis that has investigated the functional movement quality in a large, randomly selected sample of urban adolescents (sample size in Study 1, Study 2, and Study 3 ranged from 558 to 725 participants). Second, in this thesis, sophisticated statistical methods were used. In Study 1 and Study 2 the multilevel methodology was utilized, while in Study 3 ML was applied for the prediction of musculoskeletal injury. This resulted in less biased results (e.g. ecological fallacy is reduced) where clearer conclusions can be drawn. Third, a large number of predictors was controlled in analyses (age, sex, sports participation, socioeconomic status, PA level, BMI, body fat percentage) that should allow a more accurate prediction of functional movement in the adolescent population. Forth, in Study 1 number of sports was included as the potential moderators in all multilevel regression analyses, while in Study 2 adiposity was represented via four different indicators which can give deeper insight into the relation between adiposity and FM. Fifth, in this doctoral thesis subgroup analyses were employed, where sex-specific associations were investigated within Study 1 and Study 2, while in Study 3, athletic and non-athletic youth were analyzed separately. This approach gave new and valuable information about sex- and sport- specific relationships between FM, PA, adiposity indicators, and musculoskeletal injuries in the average population of adolescents.

However, there are also a few limitations that need to be considered while interpreting this data. This study investigated the population in the urban area, thus excluding children from rural areas which may affect the generalizability of the results in the context of the general adolescent population. Second, for the purpose of FMS^{TM} testing procedures, 10 raters were recruited. However, all raters underwent the same education and FMS^{TM} testing protocol. In addition, previous studies consistently showed good interrater agreement in FMS scores (Smith et al., 2013; Teyhen et al., 2012). Although we included a considerable number of injury predictors in Study 3, the previous injury was not included as the predictor in the models which can influence drawn conclusions about injury prediction. Next, injuries in this study were not assessed prospectively. Although we are aware of the potential recall bias of a self-reported injury questionnaire, a prior study has shown a perfect agreement (k = 1.00, 95% CI 1.00 to 1.00) between a prospective and a retrospective record of reported injury (yes/no answer) during a one-year period (Gabbe, Finch, Bennell, 2003). Study 1 and Study 2 have a cross-sectional design which limits causal interpretations. Furthermore, in Study 2, a higher proportion of children with obesity among boys compared to girls could drive some of the sex differences in the association of adiposity and FM reported in this thesis. However, given that this is a population-based study, this sex-difference in obesity rate was expected because they are based on the available data from the recent collation of representative studies in Croatian mid adolescents NCD Risk Factor Collaboration, 2020). Despite all this, the results of this doctoral thesis give valuable information on injury prediction, the relationship between PA, adiposity, and FM among the mid-adolescent population.

Perspective for future research

In order to determine the effect of adiposity on FM, further longitudinal and intervention studies are required to investigate the impact of obesity on FM and musculoskeletal health in a mid-adolescent population. Also, future research should focus on the investigation of the influence of different predictors of injury in the adolescent population. Since the application of a multilevel methodology and ML is lacking in this research area, the implication of the aforementioned approach for future researchers is strongly suggested. This approach will yield a more accurate prediction that in turn could be better translated into clinical practice.

Future studies should consider more precise methods in the evaluation of obesity in children. Also, future researches should include more participants with overweight and obesity and consider the usage of prospective methods of injury tracking within the non-injured population.

REFERENCES

Abassi, M., Bleakley, C., & Whiteley, R. (2019). Athletes at late stage rehabilitation have persisting deficits in plantar- and dorsiflexion, and inversion (but not eversion) after ankle sprain. *Physical Therapy in Sport*, *38*, 30–35. https://doi.org/10.1016/j.ptsp.2019.04.015

Abraham, A., Sannasi, R., & Nair, R. (2015). Normative values for the functional movement screentm in adolescent school aged children. *International Journal of Sports Physical Therapy*, *10*(1), 29–36.

Aderem, J., & Louw, Q. A. (2015). Biomechanical risk factors associated with iliotibial band syndrome in runners: A systematic review Rehabilitation, physical therapy and occupational health. *BMC Musculoskeletal Disorders*, *16*(1), 7–9. https://doi.org/10.1186/s12891-015-0808-7

Ahnert J., Schneider W, B. K. (2011). *Developmental changes and individual stability of motor abilities from the preschool period to young adulthood. In: Human devel- opment from early childhood to early adulthood: findings from a 20 year longitudinal study.* Psychology Press.

Alles, W. F., Powell, J. W., Buckley, W., & Hunt, E. E. (1979). The National Athletic Injury/Illness Reporting System 3-year findings of high school and college football injuries. *Journal of Orthopaedic and Sports Physical Therapy*, *1*(2), 103–108. https://doi.org/10.2519/jospt.1979.1.2.103

Alvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sanchez-Lopez, M., Garrido-Miguel, M., & Martinez-Vizcaino, V. (2017). Academic achievement and physical activity: A meta-analysis. *Pediatrics*, *140*(6). https://doi.org/10.1542/peds.2017-1498

Anderson, P. M., & Butcher, K. E. (2006). Childhood obesity: trends and potential causes. *The Future of children*, *16*(1), 19–45. https://doi.org/10.1353/foc.2006.0001

Araújo, F. A., Martins, A., Alegrete, N., Howe, L. D., & Lucas, R. (2017). A shared biomechanical environment for bone and posture development in children. *Spine Journal*, *17*(10), 1426–1434. https://doi.org/10.1016/j.spinee.2017.04.024

Ayer, J., Charakida, M., Deanfield, J. E., & Celermajer, D. S. (2015). Lifetime risk: Childhood obesity and cardiovascular risk. *European Heart Journal*, *36*(22), 1371–1376. https://doi.org/10.1093/eurheartj/ehv089

Baghbani, F., Woodhouse, L. J., & Gaeini, A. A. (2016). Dynamic postural control in female athletes and nonathletes after a whole-body fatigue protocol. *Journal of Strength and Conditioning Research*, *30*(7), 1942–1947. https://doi.org/10.1519/JSC.0000000000001275

Bahr, R. (2016). Why screening tests to predict injury do not work-and probably never will.: A critical review. *British Journal of Sports Medicine*, *50*(13), 776–780. https://doi.org/10.1136/bjsports-2016-096256

Bays, H. E., Toth, P. P., Kris-Etherton, P. M., Abate, N., Aronne, L. J., Brown, W. V., Gonzalez-Campoy, J. M., Jones, S. R., Kumar, R., La Forge, R., & Samuel, V. T. (2013). Obesity, adiposity, and dyslipidemia: A consensus statement from the National Lipid Association. *Journal of Clinical Lipidology*, *7*(4), 304–383. https://doi.org/10.1016/j.jacl.2013.04.001

Beaudouin, F., Rössler, R., Aus Der Fünten, K., Bizzini, M., Chomiak, J., Verhagen, E., Junge, A., Dvorak, J., Lichtenstein, E., Meyer, T., & Faude, O. (2019). Effects of the “11+ Kids” injury prevention programme on severe injuries in children’s football: A secondary analysis of data from a multicentre cluster-randomised controlled trial. *British Journal of Sports Medicine*, *53*(22), 1418–1423. https://doi.org/10.1136/bjsports-2018-099062

Bentham, J., Di Cesare, M., Bilano, V., Bixby, H., Zhou, B., Stevens, G. A., Riley, L. M., Taddei, C., Hajifathalian, K., Lu, Y., Savin, S., Cowan, M. J., Paciorek, C. J., Chirita-Emandi, A., Hayes, A. J., Katz, J., Kelishadi, R., Kengne, A. P., Khang, Y. H., … Cisneros, J. Z. (2017). Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *The Lancet*, *390*(10113), 2627–2642. https://doi.org/10.1016/S0140-6736(17)32129-3

Bitsori, M., Linardakis, M., Tabakaki, M., & Kafatos, A. (2009). Waist circumference as a screening tool for the identification of adolescents with the metabolic syndrome phenotype. *International Journal of Pediatric Obesity*, *4*(4), 325–331. https://doi.org/10.3109/17477160902914597

Biddle, S. J., Gorely, T., Pearson, N., & Bull, F. C. (2011). An assessment of self-reported physical activity instruments in young people for population surveillance: Project ALPHA. *The international journal of behavioral nutrition and physical activity*, *8*, 1. https://doi.org/10.1186/1479-5868-8-1

Blimkie, C. J. R., Sale, D. G., & Bar-Or, O. (1990). Voluntary strength, evoked twitch contractile properties and motor unit activation of knee extensors in obese and non-obese adolescent males. *European Journal of Applied Physiology and Occupational Physiology*, *61*(3–4), 313–318. https://doi.org/10.1007/BF00357619

Bloemers, F., Collard, D., Paw, M. C. A., Van Mechelen, W., Twisk, J., & Verhagen, E. (2012). Physical inactivity is a risk factor for physical activity-related injuries in children. *British Journal of Sports Medicine*, *46*(9), 669–674. https://doi.org/10.1136/bjsports-2011-090546

Boling, M. C., Padua, D. A., Marshall, S. W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009). A prospective investigation of biomechanical risk factors for Patellofemoral pain syndrome: The joint undertaking to monitor and prevent acl injury (JUMP-ACL) Cohort. *American Journal of Sports Medicine, 37*(11), 2108–2116. https://doi.org/10.1177/0363546509337934

Bonazza, N. A., Smuin, D., Onks, C. A., Silvis, M. L., & Dhawan, A. (2017). Reliability, Validity, and Injury Predictive Value of the Functional Movement Screen. *American Journal of Sports Medicine*, *45*(3), 725–732. https://doi.org/10.1177/0363546516641937

Bond, C. W., Dorman, J. C., Odney, T. O., Roggenbuck, S. J., Young, S. W., & Munce, T. A. (2019). Evaluation of the functional movement screen and a novel basketball mobility test as an injury prediction tool for collegiate basketball players. In *Journal of Strength and Conditioning Research* (Vol. 33, Issue 6). https://doi.org/10.1519/JSC.0000000000001944

Brener, N. D., Collins, J. L., Kann, L., Warren, C. W., & Williams, B. I. (1995). Reliability of the Youth Risk Behavior Survey Questionnaire. *American journal of epidemiology*, *141*(6), 575–580. https://doi.org/10.1093/oxfordjournals.aje.a117473

Bridger, T. (2009). Childhood obesity and cardiovascular disease. *Paediatrics and Child Health*, *14*(3), 177–182. https://doi.org/10.1093/pch/14.3.177

Brozek, J., F. Grande, J. T. Anderson, and A. Keys. Densitometric analysis of body composition: revision of some quantitative assumptions. Ann. NY Acad. Sci. 110: 113–140, 1963

Brzeziński, M., Czubek, Z., Niedzielska, A., Jankowski, M., Kobus, T., & Ossowski, Z. (2019). Relationship between lower-extremity defects and body mass among polish children: A cross-sectional study. *BMC Musculoskeletal Disorders*, *20*(1), 1–9. https://doi.org/10.1186/s12891-019-2460-0

Caine, D., Maffulli, N., & Caine, C. (2008). Epidemiology of injury in child and adolescent sports: injury rates, risk factors, and prevention. *Clinics in sports medicine*, *27*(1), 19–vii. https://doi.org/10.1016/j.csm.2007.10.008

Campbell, E. L., Seynnes, O. R., Bottinelli, R., McPhee, J. S., Atherton, P. J., Jones, D. A., Butler-Browne, G., & Narici, M. V. (2013). Skeletal muscle adaptations to physical inactivity and subsequent retraining in young men. *Biogerontology*, *14*(3), 247–259. https://doi.org/10.1007/s10522-013-9427-6

Martin, C., Olivier, B., & Benjamin, N. (2011). The Functional Movement Screen in the Prediction of Injury in Adolescent Cricket Pace Bowlers: An Observational Study. *Journal of sport rehabilitation*, *26*(5), 386–395. https://doi.org/10.1123/jsr.2016-0073

Caspersen, C. J., Pereira, M. A., & Curran, K. M. (2000). Changes in physical activity patterns in the United States, by sex and cross-sectional age. *Medicine and science in sports and exercise*, *32*(9), 1601–1609. https://doi.org/10.1097/00005768-200009000-00013

Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). *Association of Schools of Public Health Physical Activity , Exercise , and Physical Fitness : Definitions and Distinctions for Health- Related Research Reviewed work (s): Physical Activity , Exercise , and Physical Fitness : and Distinctions Definitions*. *100*(2), 126–131.

Catan, L., Amaricai, E., Onofrei, R. R., Popoiu, C. M., Iacob, E. R., Stanciulescu, C. M., Cerbu, S., Horhat, D. I., & Suciu, O. (2020). The impact of overweight and obesity on plantar pressure in children and adolescents: A systematic review. *International Journal of Environmental Research and Public Health*, *17*(18), 1–21. https://doi.org/10.3390/ijerph17186600

Cejudo, A., Robles-Palazón, F. J., Ayala, F., De Ste Croix, M., Ortega-Toro, E., Santonja-Medina, F., & De Baranda, P. S. (2019). Age-related differences in flexibility in soccer players 8-19 years old. *PeerJ*, *2019*(1), 1–16. https://doi.org/10.7717/peerj.6236

Centers for Disease Control and Prevention (CDC) (2006). Sports-related injuries among high school athletes--United States, 2005-06 school year. *MMWR. Morbidity and mortality weekly report*, *55*(38), 1037–1040.

Clifton, D. R., Harrison, B. C., Hertel, J., & Hart, J. M. (2013). Relationship between functional assessments and exercise-related changes during static balance. *Journal of Strength and Conditioning Research*, *27*(4), 966–972. https://doi.org/10.1519/JSC.0b013e318260b723

Cole, T. J., Bellizzi, M. C., Flegal, K. M., & Dietz, W. H. (2000). Establishing a standard definition for child overweight and obesity worldwide: International survey. *British Medical Journal*, *320*(7244), 1240–1243. https://doi.org/10.1136/bmj.320.7244.1240

Cook, G. (2011). *Movement: Functional Movement Systems: Screening, Assessment, Corrective Strategies* (1st ed.). Lotus Pub.

Cook, G., & Burton, L. (2016). *Pre-Participation Screening The Use of Fundamental Movements As An Assessment of Function Part 1*. *1*(2), 62–72.

Cook, G., Burton, L., & Hoogenboom, B. (2006a). Pre-Participation Screening: The Use of Fundamental Movements As An Assessment of Function–Part 1. *North American Journal of Sports Physical Therapy: NAJSPT*, *1*(2), 62. https://doi.org/10.1055/s-0034-1382055

Cook, G., Burton, L., & Hoogenboom, B. (2006b). Pre-Participation Screening: The Use of Fundamental Movements As An Assessment of Function–Part 2. *North American Journal of Sports Physical Therapy: NAJSPT*, *1*(2), 62. https://doi.org/10.1055/s-0034-1382055

Crocker, P. R., Bailey, D. A., Faulkner, R. A., Kowalski, K. C., & McGrath, R. (1997). Measuring general levels of physical activity: preliminary evidence for the Physical Activity Questionnaire for Older Children. *Medicine and science in sports and exercise*, *29*(10), 1344–1349. https://doi.org/10.1097/00005768-199710000-00011

Davison, K. K., & Birch, L. L. (2001). Childhood overweight: a contextual model and recommendations for future research. *Obesity reviews : an official journal of the International Association for the Study of Obesity*, *2*(3), 159–171. https://doi.org/10.1046/j.1467-789x.2001.00036.x

D'Hondt, E., Deforche, B., De Bourdeaudhuij, I., & Lenoir, M. (2008). Childhood obesity affects fine motor skill performance under different postural constraints. *Neuroscience Letters*, *440*(1), 72–75. https://doi.org/10.1016/j.neulet.2008.05.056

De La Motte, S. J., Gribbin, T. C., Lisman, P., Murphy, K., & Deuster, P. A. (2017). Systematic review of the association between physical fitness and musculoskeletal injury risk: Part 2 — Muscular endurance and muscular strength. *Journal of Strength and Conditioning Research*, *31*(11), 3218–3234. https://doi.org/10.1519/JSC.0000000000002174

De La Motte, S. J., Lisman, P., Gribbin, T. C., Murphy, K., & Deuster, P. A. (2019). Systematic review of the association between physical fitness and musculoskeletal injury risk: Part 3-Flexibility, power, speed, Balance, and agility. In *Journal of Strength and Conditioning Research* (Vol. 33, Issue 6). https://doi.org/10.1519/JSC.0000000000002382

de Silva, V., Swain, M., Broderick, C., & McKay, D. (2016). Does high level youth sports participation increase the risk of femoroacetabular impingement? A review of the current literature. *Pediatric Rheumatology*, *14*(1), 1–7. https://doi.org/10.1186/s12969-016-0077-5

Department of Health & Human Services. (2018). 2018 Physical Activity Guidelines Advisory Committee. *Physical Activity Guidelines Advisory Committee Scientific Report*, 779. https://doi.org/10.1111/j.1753-4887.2008.00136.x

Di Cesare, M., Bentham, J., Stevens, G. A., Zhou, B., Danaei, G., Lu, Y., Bixby, H., Cowan, M. J., Riley, L. M., Hajifathalian, K., Fortunato, L., Taddei, C., Bennett, J. E., Ikeda, N., Khang, Y. H., Kyobutungi, C., Laxmaiah, A., Li, Y., Lin, H. H., … Cisneros, J. Z. (2016). Trends in adult body-mass index in 200 countries from 1975 to 2014: A pooled analysis of 1698 population-based measurement studies with 19.2 million participants. *The Lancet*, *387*(10026), 1377–1396. https://doi.org/10.1016/S0140-6736(16)30054-X

Dietz, W. H., & Robinson, T. N. (1998). Use of the body mass index (BMI) as a measure of overweight in children and adolescents. *The Journal of pediatrics*, *132*(2), 191–193. https://doi.org/10.1016/s0022-3476(98)70426-3

Ding, D., Lawson, K. D., Kolbe-Alexander, T. L., Finkelstein, E. A., Katzmarzyk, P. T., van Mechelen, W., & Pratt, M. (2016). The economic burden of physical inactivity: a global analysis of major non-communicable diseases. *The Lancet*, *388*(10051), 1311–1324. https://doi.org/10.1016/S0140-6736(16)30383-X

DiFiori, J. P., Benjamin, H. J., Brenner, J., Gregory, A., Jayanthi, N., Landry, G. L., & Luke, A. (2014). Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*, *24*(1), 3–20. https://doi.org/10.1097/JSM.0000000000000060

Dolphens, M., Cagnie, B., Vleeming, A., Vanderstraeten, G., & Danneels, L. (2013). Gender differences in sagittal standing alignment before pubertal peak growth: The importance of subclassification and implications for spinopelvic loading. *Journal of Anatomy*, *223*(6), 629–640. https://doi.org/10.1111/joa.12119

Dowd, M. D., Keenan, H. T., & Bratton, S. L. (2002). Epidemiology and prevention of childhood injuries. *Critical Care Medicine*, *30*(11 SUPPL.), 385–392. https://doi.org/10.1097/00003246-200211001-00002

Duncan, M. J., Bryant, E., & Stodden, D. (2017). Low fundamental movement skill proficiency is associated with high BMI and body fatness in girls but not boys aged 6–11 years old. *Journal of Sports Sciences*, *35*(21), 2135–2141. https://doi.org/10.1080/02640414.2016.1258483

Duncan, M. J., & Stanley, M. (2012). Functional movement is negatively associated with weight status and positively associated with physical activity in British primary school children. *Journal of Obesity*, *2012*. https://doi.org/10.1155/2012/697563

Duncan, M. J., Stanley, M., & Leddington Wright, S. (2013). The association between functional movement and overweight and obesity in British primary school children. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*, *5*(1), 11. https://doi.org/10.1186/2052-1847-5-11

Emery, C. A. (2015). Risk Factors for Injury in Child and Adolescent Sport: A Systematic Review of the Literature. *British Journal of Sports Medicine*, *49*(17), 1094–1099. https://doi.org/10.1136/bjsports-2014-094372

Emery, C. A., Hagel, B., & Morrongiello, B. A. (2006). *Injury Prevention in Child and Adolescent Sport : Whose Responsibility Is It ? 16*(6), 514–521.

Emery, C. A., & Tyreman, H. (2009). Sport participation, sport injury, risk factors and sport safety practices in Calgary and area junior high schools. *Paediatrics and Child Health*, *14*(7), 439–444. https://doi.org/10.1093/pch/14.7.439

Ekegren, C. L., Gabbe, B. J., & Finch, C. F. (2016). Sports Injury Surveillance Systems: A Review of Methods and Data Quality. *Sports medicine (Auckland, N.Z.)*, *46*(1), 49–65. https://doi.org/10.1007/s40279-015-0410-z

Freedman, D. S., Wang, J., Ogden, C. L., Thornton, J. C., Mei, Z., Pierson, R. N., Dietz, W. H., & Horlick, M. (2007). The prediction of body fatness by BMI and skinfold thicknesses among children and adolescents. *Annals of human biology*, *34*(2), 183–194. https://doi.org/10.1080/03014460601116860

Friden, T., Roberts, D., Zatterstrom, R., Lindstrand, A., & Moritz, U. (1997). Proprioception after an acute knee ligament injury: A longitudinal study on 16 consecutive patients. *Journal of Orthopaedic Research*, *15*(5), 637–644. https://doi.org/10.1002/jor.1100150502

Friel, K., McLean, N., Myers, C., & Caceres, M. (2006). Ipsilateral hip abductor weakness after inversion ankle sprain. *Journal of Athletic Training*, *41*(1), 74–78.

Gabbe, B.J., Finch, C.F., Bennell, K.L., Wajswelner, H. (2003). How valid is a self reported 12 month sports injury history? *British Journal of Sports Medicine*, *37*(6), 545–547. https://doi.org/10.1136/bjsm.37.6.543

García-Pinillos, F., Roche-Seruendo, L. E., Delgado-Floody, P., Mayorga, D. J., & Latorre-Román, and Latorre-román, P. Á. (2018). Nutrición Hospitalaria Trabajo Original Is there any relationship between functional movement and weight status. *Pediatria*, *2*, 22. https://doi.org/http://dx.doi.org/10.20960/nh.1670

Garrison, M., Westrick, R., Johnson, M. R., & Benenson, J. (2015). Association between the functional movement screen and injury development in college athletes. *International Journal of Sports Physical Therapy*, *10*(1), 21–28.

Gijon-Nogueron, G., Montes-Alguacil, J., Martinez-Nova, A., Alfageme-Garcia, P., Cervera-Marin, J. A., & Morales-Asencio, J. M. (2017). Overweight, obesity and foot posture in children: A cross-sectional study. *Journal of Paediatrics and Child Health*, *53*(1), 33–37. https://doi.org/10.1111/jpc.13314

Gribble, P. A., Bleakley, C. M., Caulfield, B. M., Docherty, C. L., Fourchet, F., Fong, D. T. P., Hertel, J., Hiller, C. E., Kaminski, T. W., McKeon, P. O., Refshauge, K. M., Verhagen, E. A., Vicenzino, B. T., Wikstrom, E. A., & Delahunt, E. (2016). Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *British Journal of Sports Medicine*, *50*(24), 1496–1505. https://doi.org/10.1136/bjsports-2016-096189

Gushue, D., Lerner, A., Becerra, S., Cregan, L., Kelly, J., Vincent, A., & Houck, J. (2005). Effects of Childhood Obesity on Three-Dimensional Knee Joint Biomechanics During Walking. *Pediatric Physical Therapy*, *17*(1), 61. https://doi.org/10.1097/01.PEP.0000155629.67403.DA

Hertel, J., Buckley, W. E., & Denegar, C. R. (2001). Serial Testing of Postural Control after Acute Lateral Ankle Sprain. *Journal of Athletic Training*, *36*(4), 363–368.

Ittenbach, R. F., Buison, A. M., Stallings, V. A., & Zemel, B. S. (2006). Statistical validation of air-displacement plethysmography for body composition assessment in children. *Annals of human biology*, *33*(2), 187–201. https://doi.org/10.1080/03014460500519925

Jankowicz-Szymańska, A., Bibro, M., Wodka, K., & Smola, E. (2019). Does excessive body weight change the shape of the spine in children? *Childhood Obesity*, *15*(5), 346–352. https://doi.org/10.1089/chi.2018.0361

Janssen, LeBlanc, I. A. G. (2010). Systematic review of the health benefits of physical activity and fitness in school-aged children and youth. *International Journal of Behavioral Nutrition and Physical Activity*, *7*(40), 1–16. https://doi.org/10.1186/1479-5868-7-40

Jespersen, E., Verhagen, E., Holst, R., Klakk, H., Heidemann, M., Rexen, C. T., Franz, C., & Wedderkopp, N. (2014). Total body fat percentage and body mass index and the association with lower extremity injuries in children: A 2.5-year longitudinal study. *British Journal of Sports Medicine*, *48*(20), 1497–1501. https://doi.org/10.1136/bjsports-2013-092790

Kiesel, K. B., Butler, R. J., & Plisky, P. J. (2014). Prediction of Injury by Limited and Asymmetrical Fundamental Movement Patterns in American Football Players. *Journal of Sport Rehabilitation*, *23*(2), 88–94. https://doi.org/10.1123/JSR.2012-0130

Kiesel, K., Plisky, P. J., & Voight, M. L. (2007). Can Serious Injury in Professional Football be Predicted by a Preseason Functional Movement Screen? *North American Journal of Sports Physical Therapy : NAJSPT*, *2*(3), 147–158. https://doi.org/10.1186/2052-1847-5-11

Kowalski, K.C., Crocker, P.R.E., Kowalski, N.P. (1997) Convergent validity of the Physical Activity Questionnaire for Adolescents. *Pediatric Exercise Science*, *9*, 342-52

Kozak, A., Schedlbauer, G., Wirth, T., Euler, U., Westermann, C., & Nienhaus, A. (2015). Association between work-related biomechanical risk factors and the occurrence of carpal tunnel syndrome: An overview of systematic reviews and a meta-analysis of current research. *BMC Musculoskeletal Disorders*, *16*(1). https://doi.org/10.1186/s12891-015-0685-0

Kraus, K., Schütz, E., Taylor, W. R., & Doyscher, R. (2014). Efficacy of the functional movement screen: a review. *Journal of strength and conditioning research*, *28*(12), 3571–3584. https://doi.org/10.1519/JSC.0000000000000556

Krul, M., Van Der Wouden, J. C., Schellevis, F. G., Van Suijlekom-Smit, L. W. A., & Koes, B. W. (2009). Musculoskeletal problems in overweight and obese children. *Annals of Family Medicine*, *7*(4), 352–356. https://doi.org/10.1370/afm.1005

Lester, D., McGrane, B., Belton, S., Duncan, M., Chambers, F., & O'Brien, W. (2017). The Age-Related Association of Movement in Irish Adolescent Youth. *Sports*, *5*(4), 77. https://doi.org/10.3390/sports5040077

Lloyd, R. S., Oliver, J. L., Radnor, J. M., Rhodes, B. C., Faigenbaum, A. D., & Myer, G. D. (2015). Relationships between functional movement screen scores, maturation and physical performance in young soccer players. *Journal of Sports Sciences*, *33*(1), 11–19. https://doi.org/10.1080/02640414.2014.918642

Lonner, B. S., Toombs, C. S., Husain, Q. M., Sponseller, P., Shufflebarger, H., Shah, S. A., Samdani, A. F., Betz, R. R., Cahill, P. J., Yaszay, B., & Newton, P. O. (2015). Body Mass Index in Adolescent Spinal Deformity: Comparison of Scheuermann's Kyphosis, Adolescent Idiopathic Scoliosis, and Normal Controls. *Spine Deformity*, *3*(4), 318–326. https://doi.org/10.1016/j.jspd.2015.02.004

Maciałczyk-Paprocka, K., Stawińska-Witoszyńska, B., Kotwicki, T., Sowińska, A., Krzyżaniak, A., Walkowiak, J., & Krzywińska-Wiewiorowska, M. (2017). Prevalence of incorrect body posture in children and adolescents with overweight and obesity. *European Journal of Pediatrics*, *176*(5), 563–572. https://doi.org/10.1007/s00431-017-2873-4

Mahmoud, N. F., Hassan, K. A., Abdelmajeed, S. F., Moustafa, I. M., & Silva, A. G. (2019). The Relationship Between Forward Head Posture and Neck Pain: a Systematic Review and Meta-Analysis. *Current Reviews in Musculoskeletal Medicine*, *12*(4), 562–577. https://doi.org/10.1007/s12178-019-09594-y

Marques, V. B., Medeiros, T. M., de Souza Stigger, F., Nakamura, F. Y., & Baroni, B. M. (2017). the Functional Movement Screen (Fms) in Elite Young Soccer Players Between 14 and 20 Years: Composite Score, Individual-Test Scores and Asymmetries. *International Journal of Sports Physical Therapy*, *12*(6), 977–985. https://doi.org/10.16603/ijspt20170977

McCrory, M. A., Molé, P. A., Gomez, T. D., Dewey, K. G., & Bernauer, E. M. (1998). Body composition by air-displacement plethysmography by using predicted and measured thoracic gas volumes. *Journal of applied physiology (Bethesda, Md. : 1985)*, *84*(4), 1475–1479. https://doi.org/10.1152/jappl.1998.84.4.1475

Merder-Coşkun, D., Uzuner, A., Keniş-Coşkun, Ö., Çelenlioğlu, A. E., Akman, M., & Karadağ-Saygi, E. (2017). Relationship between obesity and musculoskeletal system findings among children and adolescents. *Turkiye Fiziksel Tip ve Rehabilitasyon Dergisi*, *63*(3), 207–214. https://doi.org/10.5606/tftrd.2017.422

Merriam-Webster. (n.d.). Adiposity. In *Merriam-Webster.com medical dictionary*. Retrieved February 18, 2021, from https://www.merriam-webster.com/medical/adiposity

Mitchell, U. H., Johnson, A. W., & Adamson, B. (2015). Relationship between functional movement screen scores, core strength, posture, and body mass index in school children in Moldova. *Journal of Strength and Conditioning Research*, *29*(5), 1172–1179. https://doi.org/10.1519/JSC.0000000000000722

Mock, C., & Cherian, M. N. (2008). The global burden of musculoskeletal injuries: Challenges and solutions. *Clinical Orthopaedics and Related Research*, *466*(10), 2306–2316. https://doi.org/10.1007/s11999-008-0416-z

Molina-Garcia, P., H Migueles, J., Cadenas-Sanchez, C., Esteban-Cornejo, I., Mora-Gonzalez, J., Rodriguez-Ayllon, M., Plaza-Florido, A., Molina-Molina, A., Garcia-Delgado, G., D'Hondt, E., Vanrenterghem, J., & Ortega, F. B. (2019). Fatness and fitness in relation to functional movement quality in overweight and obese children. *Journal of Sports Sciences*, *37*(8), 878–885. https://doi.org/10.1080/02640414.2018.1532152

Molina-Garcia, P., Migueles, J. H., Cadenas-Sanchez, C., Esteban-Cornejo, I., Mora-Gonzalez, J., Rodriguez-Ayllon, M., Plaza-Florido, A., Vanrenterghem, J., & Ortega, F. B. (2019). A systematic review on biomechanical characteristics of walking in children and adolescents with overweight/obesity: Possible implications for the development of musculoskeletal disorders. *Obesity Reviews*, *January*, 1–12. https://doi.org/10.1111/obr.12848

Molina-Garcia, P., Plaza-Florido, A., Mora-Gonzalez, J., Torres-Lopez, L. V., Vanrenterghem, J., & Ortega, F. B. (2020). Role of physical fitness and functional movement in the body posture of children with overweight/obesity. *Gait and Posture*, *80*(March), 331–338. https://doi.org/10.1016/j.gaitpost.2020.04.001

Moran, R. W., Schneiders, A. G., Mason, J., & Sullivan, S. J. (2017). Do Functional Movement Screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis. *British Journal of Sports Medicine*, *51*(23), 1661–1669. https://doi.org/10.1136/bjsports-2016-096938

NCD Risk Factor Collaboration (NCD-RisC). (2020). Height and body-mass index trajectories of school-aged children and adolescents from 1985 to 2019 in 200 countries and territories: a pooled analysis of 2181 population-based studies with 65 million participants. *The Lancet*, *396*(10261), 1511–1524. https://doi.org/10.1016/S0140-6736(20)31859-6

Nooyens, A. C., Koppes, L. L., Visscher, T. L., Twisk, J. W., Kemper, H. C., Schuit, A. J., van Mechelen, W., & Seidell, J. C. (2007). Adolescent skinfold thickness is a better predictor of high body fatness in adults than is body mass index: the Amsterdam Growth and Health Longitudinal Study. *The American journal of clinical nutrition, 85*(6), 1533–1539. https://doi.org/10.1093/ajcn/85.6.1533

O'Brien, W., Duncan, M.J., Farmer, O., Lester, D. (2017). Do Irish Adolescents Have Adequate Functional Movement Skill and Confidence? *Journal of Motor Learning and Development, 6(s2),* s301-s319.

Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: The jump-ACL Study. *American Journal of Sports Medicine*, *37*(10), 1996–2002. https://doi.org/10.1177/0363546509343200

Paszkewicz, J. R., McCarty, C. W., & Van Lunen, B. L. (2013). Comparison of Functional and Static Evaluation Tools Among Adoslecent Athletes. *Journal of Strength and Conditioning Research*, *27*(10), 2842–2850. https://doi.org/10.1519/JSC.0b013e3182815770

Patel, D. R., & Baker, R. J. (2006). Musculoskeletal injuries in sports. *Primary care*, *33*(2), 545–579. https://doi.org/10.1016/j.pop.2006.02.001

Patel, D. R., Yamasaki, A., & Brown, K. (2017). Epidemiology of sports-related musculoskeletal injuries in young athletes in United States. *Translational pediatrics, 6*(3), 160–166. https://doi.org/10.21037/tp.2017.04.08

Pfeifer, C. E., Sacko, R. S., Ortaglia, A., Monsma, E. V., Beattie, P. F., Goins, J., & Stodden, D. F. (2019). Functional Movement Screen in Youth Sport Participants: Evaluating the Proficiency Barrier for Injury. *International Journal of Sports Physical Therapy, 14*(3), 436–444. https://doi.org/10.26603/ijspt20190436

Philp, F., Blana, D., Chadwick, E. K., Stewart, C., Stapleton, C., Major, K., & Pandyan, A. D. (2018). Study of the measurement and predictive validity of the Functional Movement Screen. *BMJ Open Sport and Exercise Medicine*, *4*(1), 1–7. https://doi.org/10.1136/bmjsem-2018-000357

Pickett, W., Schmid, H., Boyce, W. F., Simpson, K., Scheidt, P. C., Mazur, J., Molcho, M., King, M. A., Godeau, E., Overpeck, M., Aszmann, A., Szabo, M., & Harel, Y. (2002). Multiple Risk Behavior and Injury. *Archives of Pediatrics & Adolescent Medicine*, *156*(8), 786. https://doi.org/10.1001/archpedi.156.8.786

Pietrobelli, A., Faith, M. S., Allison, D. B., Gallagher, D., Chiumello, G., & Heymsfield, S. B. (1998). Body mass index as a measure of adiposity among children and adolescents: a validation study. *The Journal of pediatrics*, *132*(2), 204–210. https://doi.org/10.1016/s0022-3476(98)70433-0

Pill, S., & Harvey, S. (2019). A Narrative Review of Children's Movement Competence Research 1997-2017. *Physical Culture and Sport, Studies and Research*, *81*(1), 47–74. https://doi.org/10.2478/pcssr-2019-0005

Pollen, T. R., Keitt, F., & Trojian, T. H. (2021). Do Normative Composite Scores on the Functional Movement Screen Differ Across High School, Collegiate, and Professional Athletes? A Critical Review. *Clinical journal of sport medicine: official journal of the Canadian Academy of Sport Medicine*, *31*(1), 91–102. https://doi.org/10.1097/JSM.0000000000000672

Portas, M. D., Parkin, G., Roberts, J., & Batterham, A. M. (2016). Maturational effect on Functional Movement Screen™ score in adolescent soccer players. *Journal of Science and Medicine in Sport*, *19*(10), 854–858. https://doi.org/10.1016/j.jsams.2015.12.001

Prochaska, J. J., Sallis, J. F., & Long, B. (2001). A physical activity screening measure for use with adolescents in primary care. *Archives of pediatrics & adolescent medicine*, *155*(5), 554–559. https://doi.org/10.1001/archpedi.155.5.554

Quatman-Yates, C. C., Quatman, C. E., Meszaros, A. J., Paterno, M. V., & Hewett, T. E. (2012). (2011). A systematic review of sensorimotor function during adolescence: a developmental stage of increased motor awkwardness?. *British journal of sports medicine*, *46*(9), 649–655. https://doi.org/10.1136/bjsm.2010.079616

Raj, M. (2012). Obesity and cardiovascular risk in children and adolescents. *Indian Journal of Endocrinology and Metabolism*, *16*(1), 13. https://doi.org/10.4103/2230-8210.91176

Rankin, J., Matthews, L., Cobley, S., Han, A., Sanders, R., Wiltshire, H. D., & Baker, J. S. (2016). Psychological consequences of childhood obesity: psychiatric comorbidity and prevention. *Adolescent Health, Medicine and Therapeutics*, *Volume 7*, 125–146. https://doi.org/10.2147/ahmt.s101631

Ribeiro, F., & Oliveir, J. (2011). Factors Influencing Proprioception: What do They Reveal? *Biomechanics in Applications*, pp. (323-346). IntechOpen. https://doi.org/10.5772/20335. https://www.intechopen.com/books/ biomechanics-in applications/factors-influencing-proprioception-what-dothey- reveal.

Rosendahl, K., & Strouse, P. J. (2016). Sports injury of the pediatric musculoskeletal system. *La Radiologia medica*, *121*(5), 431–441. https://doi.org/10.1007/s11547-015-0615-0

Rosenfeld, S. B., Schroeder, K., & Watkins-Castillo, S. I. (2018). The Economic Burden of Musculoskeletal Disease in Children and Adolescents in the United States. *Journal of Pediatric Orthopaedics*, *38*(4), e230–e236. https://doi.org/10.1097/BPO.0000000000001131

Sahoo, K., Sahoo, B., Choudhury, A. K., Sofi, N. Y., Kumar, R., & Bhadoria, A. S. (2015). Childhood obesity: causes and consequences. *Journal of family medicine and primary care*, *4*(2), 187–192. https://doi.org/10.4103/2249-4863.154628

Schuermans, J., Danneels, L., Van Tiggelen, D., Palmans, T., & Witvrouw, E. (2017). Proximal Neuromuscular Control Protects Against Hamstring Injuries in Male Soccer Players: A Prospective Study with Electromyography Time-Series Analysis during Maximal Sprinting. *American Journal of Sports Medicine*, *45*(6), 1315–1325. https://doi.org/10.1177/0363546516687750

Schuh-Renner, A., Canham-Chervak, M., Grier, T. L., Hauschild, V. D., & Jones, B. H. (2019). Expanding the injury definition: evidence for the need to include musculoskeletal conditions. *Public Health*, *169*, 69–75. https://doi.org/10.1016/j.puhe.2019.01.002

Schwandt P. (2011). Defining central adiposity in terms of clinical practice in children and adolescents. *International journal of preventive medicine*, *2*(1), 1–2.

Seidler, R. D. (2004). Multiple Motor Learning Experiences Enhance Motor Adaptability. *Journal of Cognitive Neuroscience*, *16*(1), 65–73. https://doi.org/10.1162/089892904322755566

Shah, B., Tombeau Cost, K., Fuller A., *et al*. (2020). Sex and gender differences in childhood obesity: contributing to the research agenda. *BMJ Nutrition, Prevention & Health*; bmjnph-2020-000074. doi: 10.1136/bmjnph-2020-000074

Shojaedin, S. S., Letafatkar, A., Hadadnezhad, M., & Dehkhoda, M. R. (2014). Relationship between functional movement screening score and history of injury and identifying the predictive value of the FMS for injury. *International Journal of Injury Control and Safety Promotion*, *21*(4), 355–360. https://doi.org/10.1080/17457300.2013.833942

Silva, B., Rodrigues, L. P., Clemente, F. M., Cancela, J. M., & Bezerra, P. (2019). Association between motor competence and functional movement screen scores. *PeerJ*, *2019*(8), 1–18. https://doi.org/10.7717/peerj.7270

Singh, A. S., Mulder, C., Twisk, J. W. R., Van Mechelen, W., & Chinapaw, M. J. M. (2008). Tracking of childhood overweight into adulthood: A systematic review of the literature. *Obesity Reviews*, *9*(5), 474–488. https://doi.org/10.1111/j.1467-789X.2008.00475.x

Smith, C. A., Chimera, N. J., Wright, N. J., & Warren, M. (2013). Interrater and intrarater reliability of the functional movement screen. *J Strength Cond Res*, *27*(4), 982–987. https://doi.org/10.1519/JSC.0b013e3182606df2

Spolidoro, J. V., Pitrez Filho, M. L., Vargas, L. T., Santana, J. C., Pitrez, E., Hauschild, J. A., Bruscato, N. M., Moriguchi, E. H., Medeiros, A. K., & Piva, J. P. (2013). Waist circumference in children and adolescents correlate with metabolic syndrome and fat deposits in young adults. *Clinical nutrition (Edinburgh, Scotland)*, *32*(1), 93–97. https://doi.org/10.1016/j.clnu.2012.05.020

Stodden, D. F., Langendorfer, S. J., Goodway, J. D., Roberton, M. A., Rudisill, M. E., Garcia, C., & Garcia, L. E. (2008). A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship. *Quest*, *60*(2), 290–306. https://doi.org/10.1080/00336297.2008.10483582

Storm, J. M., Wolman, R., Bakker, E. W. P., & Wyon, M. A. (2018). The relationship between range of motion and injuries in adolescent dancers and sportspersons: A systematic review. *Frontiers in Psychology*, *9*(MAR). https://doi.org/10.3389/fpsyg.2018.00287

Taylor, W. C., & Sallis, J. F. (1997). Determinants of physical activity in children. *World Review of Nutrition and Dietetics*, *82*, 159–167. https://doi.org/10.1159/000059628

Teyhen, D. S., Shaffer, S. W., Lorenson, C. L., Halfpap, J. P., Donofry, D. F., Walker, M. J., Dugan, J. L., & Childs, J. D. (2012). The Functional Movement Screen: A Reliability Study. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(6), 530–540. https://doi.org/10.2519/jospt.2012.3838

Thivel, D., Tremblay, A., Genin, P. M., Panahi, S., Rivière, D., & Duclos, M. (2018). Physical Activity, Inactivity, and Sedentary Behaviors: Definitions and Implications in Occupational Health. *Frontiers in Public Health*, *6*(October), 1–5. https://doi.org/10.3389/fpubh.2018.00288

Tsiros, M. D., Tian, E. J., Shultz, S. P., Olds, T., Hills, A. P., Duff, J., & Kumar, S. (2020). Obesity, the new childhood disability? An umbrella review on the association between adiposity and physical function. *Obesity Reviews*, *June*, 1–13. https://doi.org/10.1111/obr.13121

van Mechelen, W., Hlobil, H., & Kemper, H. C. G. (1992). Incidence, severity, aetiology and prevention of sports injuries. *Sports Medicine*, *14*(2), 82–99.

Walsh, S. S., & Jarvis, S. N. (1992). Measuring the frequency of " severe " accidental injury in childhood. 26–32. *Journal of epidemiology and community health*, *46*(1), 26–32. https://doi.org/10.1136/jech.46.1.26

Warren, M., Lininger, M., Chimera, N., & Smith, C. (2018). Utility of FMS to understand injury incidence in sports: current perspectives. *Open Access Journal of Sports Medicine*, *Volume 9*, 171–182. https://doi.org/10.2147/oajsm.s149139

Weihrauch-Blüher, S., Schwarz, P., & Klusmann, J. H. (2019). Childhood obesity: increased risk for cardiometabolic disease and cancer in adulthood. *Metabolism: Clinical and Experimental*, *92*, 147–152. https://doi.org/10.1016/j.metabol.2018.12.001

Wells, J. C., & Fewtrell, M. S. (2006). Measuring body composition. *Archives of disease in childhood*, *91*(7), 612–617. https://doi.org/10.1136/adc.2005.085522

Widhalm, H. K., Seemann, R., Hamboeck, M., Mittlboeck, M., Neuhold, A., Friedrich, K., Hajdu, S., & Widhalm, K. (2016). Osteoarthritis in morbidly obese children and adolescents, an age-matched controlled study. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(3), 644–652. https://doi.org/10.1007/s00167-014-3068-4

Williams, J. M., Currie, C. E., Wright, P., Elton, R. A., Beattie, T. F., Pickett, W., Schmid, H., Boyce, W. F., Simpson, K., Scheidt, P. C., Mazur, J., Molcho, M., King, M. A., Godeau, E., Overpeck, M., Aszmann, A., Szabo, M., & Harel, Y. (1996). Socioeconomic status and adolescent injuries. *Soc Sci Med*, *44*(12), 1881–1891. https://doi.org/10.1016/s0277-9536(96)00297-3

Wong, S. L., Leatherdale, S. T., & Manske, S. (2006). Reliability and validity of a school-based physical activity questionnaire. *Medicine and Science in Sports and Exercise*, *38*(9), 1593–1600. https://doi.org/10.1249/01.mss.0000227539.58916.35

World Health Organization. (2020). WHO Guidelines on physical activity, sedentary behaviour. *World Health Organization*, 104.

Wright, M. D., & Chesterton, P. (2019). Functional Movement Screen TM total score does not present a gestalt measure of movement quality in youth athletes. *Journal of Sports Sciences*, *37*(12), 1393–1402. https://doi.org/10.1080/02640414.2018.1559980

Wrotniak, B. H., Epstein, L. H., Dorn, J. M., Jones, K. E., & Kondilis, V. A. (2006). The relationship between motor proficiency and physical activity in children. *Pediatrics*, *118*(6). https://doi.org/10.1542/peds.2006-0742

Wu, N., Chen, Y., Yang, J., & Li, F. (2017). Childhood obesity and academic performance: The role of working memory. *Frontiers in Psychology*, *8*, 611, 1–7. https://doi.org/10.3389/fpsyg.2017.00611

APPENDICES

Within this doctoral thesis, two studies were supplied with the appendices. In Study 1, Appendix 1 presents the results of a posteriori analysis. In Study 2, within Appendix A three figures are attached. The term Appendix A was used in Study 2 according to the official guidelines proposed by the journal in which this study was published. Therefore, to avoid possible confusion, the same terms were used for particular appendix through the text. In the next pages, the aforementioned appendices are attached.

STUDY 1 APPENDIX

(APPENDIX 1: Results of a posteriori analysis)

Results of a posteriori analysis for girls

Table A1. *Level-two models for predictor MVPA in girls, including type of PA.*

	Model 1	**S.E.**	**p-value**	**Model 2**	**S.E.**	**p-value**	**Model 3**	**S.E.**	**p-value**	**Model 4**	**S.E.**	**p-value**
Response	Total FMS score			Total FMS score			Total FMS score			Total FMS score		
Fixed Part												
cons	12.141	0.747	0.000	12.095	0.744	0.000	12.154	0.743	0.000	12.111	0.740	0.000
MVPA	**0.005**	**0.002**	**0.006**	**0.005**	**0.002**	**0.007**	**0.005**	**0.002**	**0.009**	**0.004**	**0.002**	**0.011**
%BF	0.017	0.023	0.479	0.015	0.023	0.509	0.016	0.023	0.484	0.015	0.023	0.512
SES	-0.055	0.164	0.739	-0.040	0.164	0.806	-0.069	0.163	0.674	-0.054	0.163	0.740
(Age-17)	0.296	0.365	0.417	0.311	0.364	0.393	0.367	0.364	0.313	0.378	0.363	0.298
Volleyball				0.944	0.554	0.089				0.875	0.551	0.112
Dance							0.927	0.481	0.054	0.875	0.480	0.068
Random Part												
Level 2: class												
Var(cons)	0.743	0.322		0.677	0.307		0.856	0.346		0.782	0.330	
Level 1: students												
Var(cons)	4.750	0.410		4.735	0.409		4.642	0.401		4.634	0.400	
Units: class	46			46			46			46		
Units: students	308			308			308			308		
Estimation:	IGLS			IGLS			IGLS			IGLS		
-2*loglikelihood:	1384.454			1.381.603			1.380.884			1.378.410		

Cons: intercept; total FMS score: Total Functional Movement Screen Score; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; MVPA: Moderate-to-Vigorous Physical Activity; SES: socioeconomic status; S.E.: Standard Error; Var: Variance.

Table A2. *Level-two models for predictor MPA in girls, including type of PA.*

	Model 1	**S.E.**	**p-value**	**Model 2**	**S.E.**	**p-value**	**Model 3**	**S.E.**	**p-value**	**Model 4**	**S.E.**	**p-value**
Response	Total FMS score			Total FMS score			Total FMS score			Total FMS score		
Fixed Part												
cons	12.620	0.729	0.000	12.587	0.724	0.000	12.510	0.727	0.000	12.487	0.723	0.000
MPA	**0.004**	**0.003**	**0.157**	**0.003**	**0.003**	**0.166**	**0.004**	**0.003**	**0.116**	**0.004**	**0.003**	**0.125**
%BF	0.017	0.024	0.472	0.017	0.023	0.478	0.016	0.024	0.503	0.016	0.023	0.507
SES	-0.103	0.164	0.529	-0.115	0.163	0.482	-0.083	0.164	0.612	-0.095	0.163	0.560
(Age-17)	0.355	0.368	0.336	0.428	0.366	0.243	0.362	0.367	0.323	0.430	0.365	0.238
Volleyball							1.084	0.560	0.053	1.003	0.556	0.071
Dance				1.035	0.482	0.032				0.972	0.481	0.043
Random Part												
Level 2: class												
Var(cons)	0.755	0.330		0.872	0.352		0.679	0.310		0.787	0.331	
Level 1: students												
Var(cons)	4.839	0.421		4.712	0.408		4.813	0.415		4.697	0.406	
Units: class	46			46			46			46		
Units: students	308			308			308			308		
Estimation:	IGLS			IGLS			IGLS			IGLS		
-2*loglikelihood	1390.059			1.385.628			1.386.376			1.382.442		

Cons: intercept; total FMS score: Total Functional Movement Screen Score; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; MPA: Moderate Physical Activity; SES: socioeconomic status; S.E.: Standard Error; Var: Variance.

Table A3. *Level-two models for predictor VPA in girls, including type of PA.*

	Model 1	**S.E.**	**p-value**	**Model 2**	**S.E.**	**p-value**	**Model 3**	**S.E.**	**p-value**	**Model 4**	**S.E.**	**p-value**
Response	Total FMS score			Total FMS score			Total FMS score			Total FMS score		
Fixed Part												
cons	12.115	0.732	0.000	12.123	0.730	0.000	12.142	0.729	0.000	12.150	0.728	0.000
VPA	**0.011**	**0.003**	**0.001**	**0.010**	**0.003**	**0.003**	**0.010**	**0.003**	**0.003**	**0.009**	**0.003**	**0.006**
%BF	0.015	0.023	0.518	0.014	0.023	0.540	0.015	0.023	0.519	0.014	0.023	0.539
SES	-0.027	0.164	0.870	-0.021	0.164	0.896	-0.043	0.164	0.792	-0.037	0.163	0.820
(Age-17)	0.326	0.362	0.368	0.340	0.362	0.347	0.389	0.361	0.281	0.401	0.361	0.266
Volleyball				0.697	0.562	0.215				0.653	0.559	0.243
Dance							0.828	0.483	0.086	0.801	0.482	0.096
Random Part												
Level 2: class												
Var(cons)	0.744	0.322		0.690	0.309		0.847	0.343		0.789	0.329	
Level 1: students												
Var(cons)	4.704	0.406		4.704	0.406		4.611	0.399		4.615	0.399	
Units: class	46			46			46			46		
Units:students	308			308			308			308		
Estimation:	IGLS			IGLS			IGLS			IGLS		
-2*loglikelihood	1.381.621			1.380.110			1.378.795			1377.458		

Cons: intercept; total FMS score: Total Functional Movement Screen Score; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; VPA: Vigorous Physical Activity; SES: socioeconomic status; S.E.: Standard Error;; Var: Variance.

Results of a posteriori analysis for boys

Table A4. *Level-two models for predictor MVPA in boys, including type of PA.*

	Model 1	S.E.	p-value	Model 2	S.E.	p-value	Model 3	S.E.	p-value	Model 4	S.E.	p-value	Model 5	S.E.	p-value
Response	Total FMS score			Total FMS score			Total FMS score			Total FMS score			Total FMS score		
Fixed Part															
cons	12.377	0.630	0.000	12.495	0.638	0.000	12.374	0.632	0.000	12.361	0.633	0.000	12.471	0.641	0.000
MPA	**-0.002**	**0.002**	**0.469**	**-0.002**	**0.002**	**0.490**	**-0.002**	**0.002**	**0.467**	**-0.002**	**0.002**	**0.463**	**-0.002**	**0.002**	**0.475**
%BF	0.009	0.019	0.651	0.008	0.019	0.663	0.009	0.019	0.649	0.009	0.019	0.657	0.008	0.019	0.663
SES	-0.068	0.162	0.676	-0.093	0.163	0.571	-0.068	0.162	0.677	-0.063	0.163	0.700	-0.088	0.164	0.592
(Age-17)	0.031	0.351	0.930	-0.008	0.353	0.982	0.032	0.352	0.927	0.039	0.352	0.912	0.004	0.354	0.992
Football				-0.400	0.349	0.252							-0.412	0.354	0.244
Basketball							0.035	0.467	0.941				0.126	0.473	0.790
Combat sports										0.150	0.522	0.774	0.129	0.521	0.805
Random Part															
Level 2: class															
Var(cons)	0.631	0.306		0.587	0.296		0.631	0.306		0.626	0.305		0.580	0.294	
Level 1: students															
Var(cons)	5.491	0.458		5.493	0.458		5.491	0.458		5.492	0.458		5.494	0.458	
Units: class	51			51			51			51			51		
Units: students	331			331			331			331			331		
Estimation:	IGLS			IGLS			IGLS			IGLS			IGLS		
-2*loglikeli-hood	1529.750			1.528.464			1.529.745			1.529.668			1.528.332		

Cons: intercept; total FMS score: Total Functional Movement Screen Score; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; MVPA: Moderate-to-Vigorous Physical Activity; SES: socioeconomic status; S.E.: Standard Error; Var: Variance.

Table A5. *Level-two models for predictor MPA in boys, including type of PA.*

	Model 1	**S.E.**	**p-value**	**Model 2**	**S.E.**	**p-value**	**Model 3**	**S.E.**	**p-value**	**Model 4**	**S.E.**	**p-value**	**Model 5**	**S.E.**	**p-value**
Response	Total FMS score			Total FMS score			Total FMS score			Total FMS score			Total FMS score		
Fixed Part															
cons	12.377	0.630	0.000	12.495	0.638	0.000	12.374	0.632	0.000	12.361	0.633	0.000	12.471	0.641	0.000
%BF	0.009	0.019	0.651	0.008	0.019	0.663	0.009	0.019	0.649	0.009	0.019	0.657	0.008	0.019	0.663
SES	-0.068	0.162	0.676	-0.093	0.163	0.571	-0.068	0.162	0.677	-0.063	0.163	0.700	-0.088	0.164	0.592
(Age-17)	0.031	0.351	0.930	-0.008	0.353	0.982	0.032	0.352	0.927	0.039	0.352	0.912	0.004	0.354	0.992
MPA	**-0.002**	**0.002**	**0.469**	**-0.002**	**0.002**	**0.490**	**-0.002**	**0.002**	**0.467**	**-0.002**	**0.002**	**0.463**	**-0.002**	**0.002**	**0.475**
Football				-0.400	0.349	0.252							-0.412	0.354	0.244
Basketball							0.035	0.467	0.941				0.126	0.473	0.790
Combat sports										0.150	0.522	0.774	0.129	0.521	0.805
Random Part															
Level 2: class															
Var(cons)	0.631	0.306		0.587	0.296		0.631	0.306		0.626	0.305		0.580	0.294	
Level 1: students															
Var(cons)	5.491	0.458		5.493	0.458		5.491	0.458		5.492	0.458		5.494	0.458	
Units: class	51			51			51			51			51		
Units: students	331			331			331			331			331		
Estimation:	IGLS			IGLS			IGLS			IGLS			IGLS		
-2*loglikelih-ood	1529.750			1.528.464			1.529.745			1.529.668			1.528.332		

Cons: intercept; total FMS score: Total Functional Movement Screen Score; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; MPA: Moderate Physical Activity; SES: socioeconomic status; S.E.: Standard Error; Var: Variance.

Table A6. *Level-two models for predictor VPA in boys, including type of PA.*

	Model 1	S.E.	p-value	Model 2	S.E.	p-value	Model 3	S.E.	p-value	Model 4	S.E.	p-value	Model 5	S.E.	p-value
Response	Total FMS score			Total FMS score			Total FMS score			Total FMS score			Total FMS score		
Fixed Part															
cons	11.908	0.651	0.000	11.980	0.650	0.000	11.912	0.651	0.000	11.899	0.653	0.000	11.974	0.652	0.000
VPA	**0.004**	**0.003**	**0.173**	**0.005**	**0.003**	**0.084**	**0.004**	**0.003**	**0.169**	**0.004**	**0.003**	**0.177**	**0.005**	**0.003**	**0.089**
%BF	0.007	0.019	0.728	0.006	0.019	0.767	0.007	0.019	0.734	0.007	0.019	0.732	0.006	0.019	0.768
SES	-0.006	0.165	0.973	-0.026	0.165	0.876	-0.005	0.165	0.975	-0.003	0.166	0.987	-0.024	0.166	0.885
(Age-17)	0.087	0.353	0.806	0.050	0.353	0.887	0.084	0.354	0.812	0.092	0.354	0.796	0.053	0.354	0.880
Football				-0.570	0.361	0.114							-0.569	0.364	0.118
Basketball							-0.089	0.471	0.850				0.010	0.473	0.983
Combat sports										0.097	0.521	0.853	0.055	0.520	0.915
Random Part															
Level 2: class															
Var(cons)	0.661	0.312		0.599	0.297		0.663	0.312		0.658	0.311		0.598	0.297	
Level 1: students															
Var(cons)	5.451	0.455		5.443	0.454		5.450	0.455		5.453	0.455		5.443	0.454	
Units: class	51			51			51			51			51		
Units: students	331			331			331			331			331		
Estimation:	IGLS			IGLS			IGLS			IGLS			IGLS		
-2*loglikel-ihood:	1528.433			1.525.980			1.528.397			1.528.398			1.525.968		

Cons: intercept; total FMS score: Total Functional Movement Screen Score; % Body Fat: Percentage of Body Fat; (Age-17): age centered around the value of 17; VPA: Vigorous Physical Activity; SES: socioeconomic status; S.E.: Standard Error; Var: Variance.

STUDY 2 APPENDIX

(APPENDIX A)

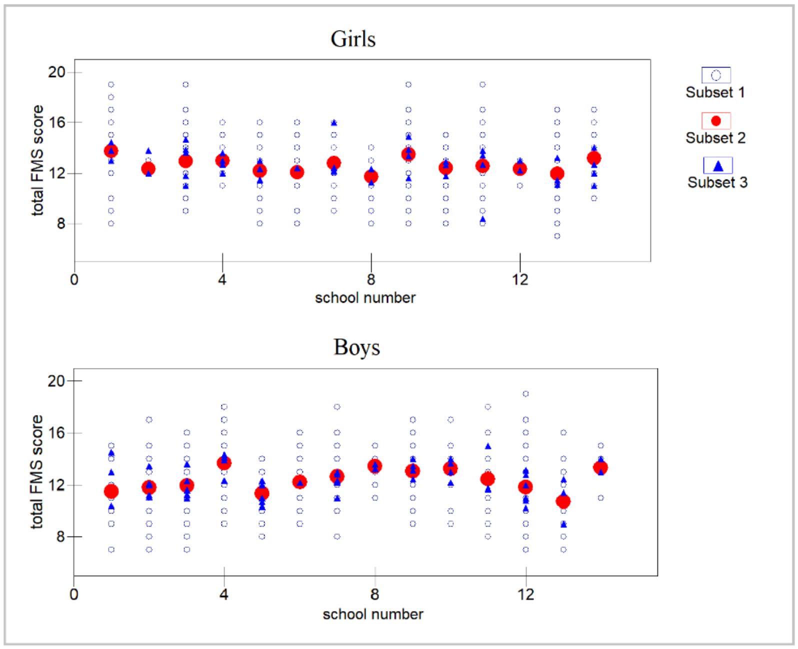

Figure A1. Total FMS score represented for each class and school (each school is represented with different number). Note: subset 1–students; subset 2-classes; Subset 3-schools.

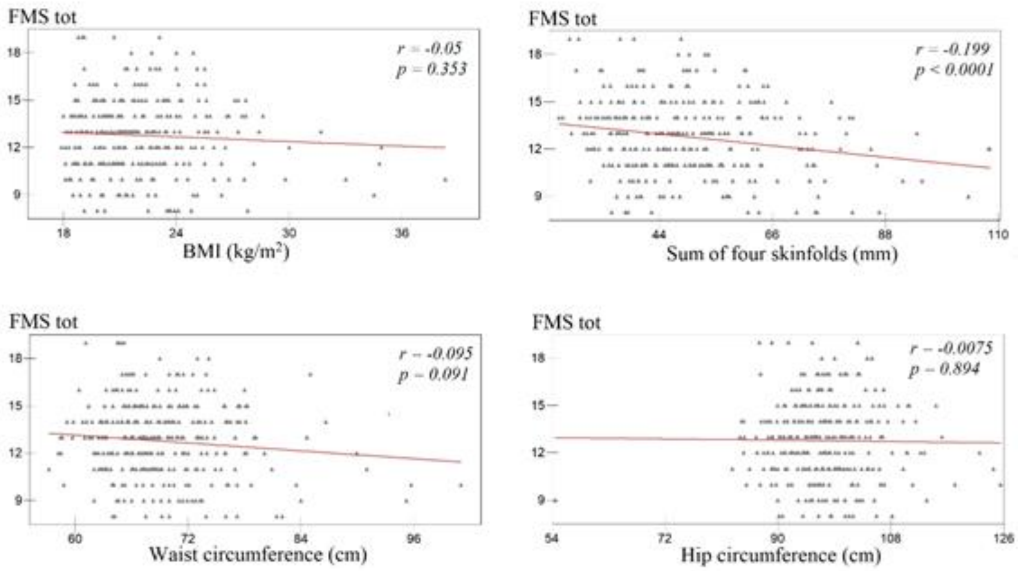

Figure A2. Correlation between BMI, sum of four skinfolds, waist and hip circumference and total FMS score among girls.

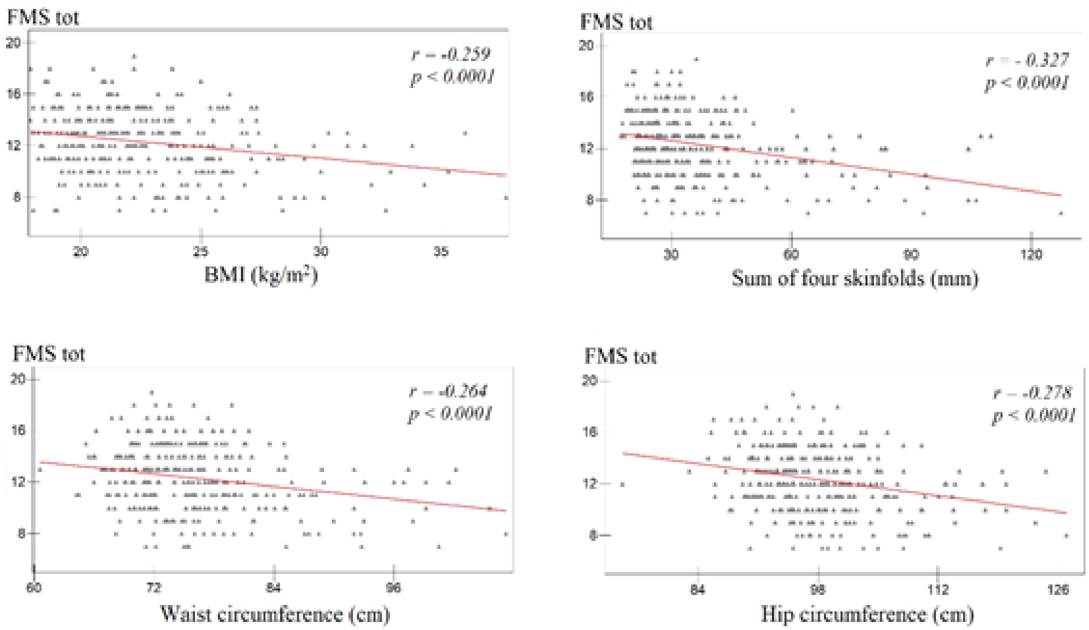

Figure A3. Correlation between BMI, sum of four skinfolds, waist and hip circumference and total FMS score among boys.

Biography

Josip Karuc is born on February 2nd 1993 in Zadar, Croatia. During his early age, while he was training diving, he showed large interest in studying sport and movement. He went to primary and secondary school in Zadar, while 2011 he moved to city of Zagreb to study Kinesiology. During his university education, he earned five Scholarships for especially talented students' – Ministry of Science, Education and Sport, Republic of Croatia. After receiving Master degree in Kinesiology in 2017, he involved in postgraduate doctoral study of Kinesiology. Currently, he is working as a young researcher at the Physical Activity Measurement and Surveillance Laboratory at the Faculty of Kinesiology, University of Zagreb. His main scientific interests relate to the investigation of the measurement of physical activity level and dysfunctional movement patterns in the adolescent population. Up to date he has published 7 scientific papers in journals indexed in the Web of Science, where he has published 6 as the first author, and five of which he has published in journals located in the first and second quartiles. Also, as a member of the CRO-PALS research team, he is currently working on the researches related to the influence of the COVID-19 pandemic lockdown on physical activity level among young adults. Along with the scientific interests, Josip is actively involved in clinical practice as well. With his colleagues, Grgur Kovačić and Nino Kecman, Josip is co-founder and co-owner of the Proprio Centar, physical therapy and sport clinic, established in 2018 in Zadar, Croatia. In his private practice, as a kinesiotherapist, he is mainly focused on the patients with the musculoskeletal injuries and chronic back pain problems. In the free time, he spends time with his family and friends, reading, drawing, travelling, and engaging in various sport activities - basketball, running, tennis, and climbing.

Curriculum vitae

Personal information

Croat, born on February 3rd in Zadar, Croatia.

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Mother tongue: Croatian. Other languages: English (advanced).

Education

1999 – 2007 Primary school education; Primary school Kruno Krstić, Zadar, Croatia

2007 – 2011 Secondary school education; High School Vladimir Nazor, Zadar, Croatia

2011 – 2016 Integrated graduated study in Kinesiology, Master's degree in Kinesiology; Faculty of Kinesiology, University of Zagreb, Zagreb, Croatia

2017 - 2021 Postgraduate doctoral study of Kinesiology; Faculty of Kinesiology, University of Zagreb, Zagreb, Croatia

Grants and awards

2011 – Best student of generation award (Class: 2010/11), High School Vladimir Nazor, Zadar, Croatia

2011 – 2016 ‘Scholarship for especially talented students’ – Ministry of Science, Education and Sport, Republic of Croatia

2020 – Best Presentation award ICPEPMH 2020: XIV. International Conference on Paediatric Exercise Physiology, Medicine and Health, London, United Kingdom, August 20-21, 2020.

Occupational activities

01/10/2018 – Present: Research and Teaching Associate; University of Zagreb, School of Kinesiology, Zagreb, Horvacanski zavoj 15, Croatia

Selected publications:

Karuc, J., & Mišigoj-Duraković, M. (2019). Relation between Weight Status, Physical activity, Maturation, and Functional Movement in Adolescence: An Overview. *Journal of functional morphology and kinesiology*, *4*(2), 31. https://doi.org/10.3390/jfmk4020031

Karuc J., Sorić M., Radman I., Mišigoj-Duraković M. (2020). Moderators of Change in Physical Activity Levels during Restrictions Due to COVID-19 Pandemic in Young Urban Adults. *Sustainability*, *12*(16), 6392. https://doi.org/10.3390/su12166392

Karuc, J., Jelčić, M., Sorić, M., Mišigoj-Duraković, M., & Marković, G. (2020). Does Sex Dimorphism Exist in Dysfunctional Movement Patterns during the Sensitive Period of Adolescence?. *Children (Basel, Switzerland)*, *7*(12), 308. https://doi.org/10.3390/children7120308

Podnar, H., Jurić, P., **Karuc, J.**, Saez, M., Barceló, M. A., Radman, I., Starc, G., Jurak, G., Đurić, S., Potočnik, Ž. L., & Sorić, M. (2021). Comparative effectiveness of school-based interventions targeting physical activity, physical fitness or sedentary behaviour on obesity prevention in 6- to 12-year-old children: A systematic review and meta-analysis. *Obesity reviews : an official journal of the International Association for the Study of Obesity*, *22*(2), e13160. https://doi.org/10.1111/obr.13160

Karuc, J., Mišigoj-Duraković, M., Marković, G., Hadžić, V., Duncan, M. J., Podnar, H., & Sorić, M. (2020). Movement quality in adolescence depends on the level and type of physical activity. *Physical therapy in sport: official journal of the Association of Chartered Physiotherapists in Sports Medicine*, *46*, 194–203. https://doi.org/10.1016/j.ptsp.2020.09.006

Karuc, J., Marković, G., Mišigoj-Duraković, M., Duncan, M. J., & Sorić, M. (2020). Is Adiposity Associated with the Quality of Movement Patterns in the Mid-Adolescent Period?. *International journal of environmental research and public health*, *17*(24), 9230. https://doi.org/10.3390/ijerph17249230

Karuc, J., Mišigoj-Duraković, M., Šarlija, M., Marković, G., Hadžić, V., Trošt-Bobić, T., Sorić, M. (2021). Can Injuries Be Predicted via Functional Movement Screen in Adolescents? The Application of Machine Learning. *Journal of Strength and Conditioning Research, Online ahead of print.* 10.1519/JSC.0000000000003982 (accepted on December 28, 2020)