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ABSTRACT

Purpose: The sudden rise in the injury incidence during adolescence, is also evident in soccer related injuries to the groin. Submaximal passing applies high stress on the adductor muscles and pubic symphysis and is therefore likely to be connected to the occurrence of groin injuries. Therefore, the purpose of the study was to compare hip joint kinematics and adductor muscle forces of different adolescent age groups during submaximal soccer passing.

Methods: Sixty participants, in four groups, below 12, 15, 16 and 23 years (U12, U15, U16, U23), were analyzed. A Footbonaut, equipped with a 3D motion capture system consisting of 16 cameras, was used to capture kinematic data of short passes. Inverse dynamic analysis was performed to calculate muscle forces of ten passes of each subject.

Results: The U15 group showed reduced angular velocities. A rise in hip adductor muscle forces was evident from the youngest group up to the oldest groups. The largest increase (49%) was found between U12 and U15. Lower limb mass was identified as the best predictor for the increasing adductor force.

Conclusion: The reduced angular velocities of the U15 and the increase in muscle forces between all age groups was attributed to the increasing segment masses and length. This increases the moments of inertia of the leg segments thereby demanding higher forces to accelerate the segments. Most likely, the stress put upon the adductors apophyses increases during adolescence, as tendons are known to adapt slower than muscles, increasing the risk for overuse injuries. Coaches could use lower limb mass as an indicator for fast increases in the force demand to identify players who would benefit from a reduced training volume. **Key Words:** Sports (MeSH), Biomechanical Phenomena (MeSH), Sprains and Strains (MeSH), Growth and Development (MeSH), Wounds and Injuries (MeSH), Football

INTRODUCTION

The incidence of sports injuries among children is generally low until the beginning of puberty. It has been reported that young soccer players have a constant injury incidence of 10 to 20% until the age of 14 after which it more than doubles (>40%) (1). A similar rise has been shown for different types of injuries and different injury locations (2–4). Among other reasons for this increase, a more aggressive playing style, greater risk-taking, lack of coordination (1), as well as participating in organized competitive sports (2) have been named. While some of the observed injuries might be considered minor injuries with no long-term effect, injuries of the groin region can have tremendous negative effects on the person concerned because of their characteristics as often having consequential damages (5,6) and increasing the risk for future groin injuries (7). Apart from the above-mentioned speculations regarding the reasons, there exists no biomechanical evidence to the underlying cause for the adolescent injury increase.

Groin injuries are one of the most frequent types of injuries among soccer players (8,9). The term 'groin injury' covers a wide range of injuries (7) with osteitis pubis and adductor strains or tears being the most prominent subcategories (10). Data demonstrating a rise in the groin specific injury incidence is limited with only one study investigating the specific incidence between age groups (3). Although this study found only six groin injuries in total in the investigated population, they were all found in players aged 13 or older. Therefore, it is plausible that an increase in the incidence as described above is also evident in groin injuries. A previous groin injury has been shown to increase the risk for future groin injuries (11,12) and two studies found recurring groin injuries in 17% of previously injured players (10,13). Furthermore, reoccurring groin injuries often lead to longer absence from training than primary injuries (12). Young players sustaining a groin injury early in their soccer career are thereby more susceptible to re-injury (10) and might suffer an early end of their career or sports participation. Therefore, identifying the underlying mechanisms leading to the abrupt rise in injury incidence is crucial to provide a basis for injury prevention and rehabilitation.

A growing body of literature acknowledges that repetitive movements such as kicking, quick changes of direction and fast accelerations could be a contributing factor to the onset of groin injuries (14–16). While all of these movements are frequently performed in soccer, only passing has been investigated regarding the load these movements induce on the musculoskeletal system (17). Results from this study showed, that musculus gracilis in particular, is subject to high muscle stress during submaximal inside passing. Gracilis and its adjacent muscle, adductor longus, are the most affected muscles in groin injuries (18). As both are attached to the pubic symphysis through the inferior pubic ligament, their combined forces are acting on this ligament. Furthermore, because the apophysis has a smaller cross-sectional area than the muscles, the stress that is applied here is substantially higher (17). When considering that passing is the most-frequently performed action during soccer play (19), the adductor muscles, and especially their tendons, experience repetitive high stresses, thus accumulating high loads during games and training. This accumulation could explain the high incidence of overuse injuries in the groin region (16) in adults, but does not explain why adolescents below the age of 15 are much less affected by injuries in general and groin injuries specifically.

The accumulation of high loads could put adolescent players under an increased risk during their growth spurt, when their body proportions are changing fast and their body is already busy adapting to these change (20). This might induce changes in movement techniques due to fast changes in the anthropometrics. Only a limited number of studies have investigated kicking mechanics of adolescent soccer players (21,22) while no study has compared soccer kicking or passing mechanics between adults and younger players. Potential alterations from the adult kinematics or kinetics in combination with changes in the anthropometrics could increase the load on the musculoskeletal structures of the groin area, hinting at reasons for the abrupt increase in injury incidence during adolescence.

Therefore, the purpose of this study was to compare the hip joint kinematics and calculated muscle forces of adductor longus and gracilis between four different age groups of soccer players performing soccer inside passing. Additionally, the potential influence of the lower limb anthropometrics on the calculated muscle forces was investigated.

METHODS

Design

A cross-sectional design was used to investigate if hip joint kinematics and adductor muscle force development differs between age groups in soccer. A three-dimensional (3D) motion capture system was used to collect kinematic data. From this, an inverse dynamics approach was utilized to calculate hip adductor muscle forces of four different age groups. The following parameters were investigated: Lower extremity anthropometrics, 3D hip joint kinematics (angles and angular velocities) and forces of the muscles adductor longus and gracilis.

Participants

Testing for the present study was performed on the training grounds of TSG 1899 Hoffenheim, one of Germany's highest-ranking soccer clubs. Sixty-Three healthy male participants, without any recent acute injuries to the lower extremities, from three different TSG academy teams (U12, U15, U16) and their second team (U23) were tested for this study. Three participants had to be excluded due to marker loss during testing or too few completed passes with their dominant leg. The number of participants per group and their anthropometrics are presented group wise in Table 1. Each participant and, if necessary, his legal guardian gave written consent prior to participation. For this purpose, underage participants received a separate information letter, specifically worded for children. The study was designed in accordance with the Declaration of Helsinki and approved by the German Sport University's ethics committee (No. 125/2016).

Procedure

In addition to the information letter, the testing procedure and measurement equipment to be used was explained in detail to the participants before physical preparation. Afterwards, 41 anthropometric measurements of each participant were taken, which were later used to scale the musculoskeletal model (see Table, Supplemental Digital Content 1, which presents an overview and detailed explanations of the anthropometric measurements, http://links.lww.com/MSS/B859). Seventy-one retro-reflective markers were attached to anatomical reference points on the participants' skin. Markers on the toe and inside of the foot were temporarily attached for the standing reference trial. These were removed immediately after the reference to allow for unhindered passing during the dynamic measurement. Participants were instructed to perform an individual warm-up prior to the measurement. U12 players were instructed during warm-up by their coach.

All data was collected in a Footbonaut, which is a ball machine for soccer-players. A detailed description of it can be found in a previous publication (17). The methods employed there were the same as in the present study except for the following differences: Every player performed a preliminary session of ten passes inside the Footbonaut to conclude the warm-up. During the actual testing, participants performed a standardized session consisting of 32 passes. Although the order of passes was standardized, participants were not familiar with the protocol, implying that the order seemed random to them. The target field could be on any side of the Footbonaut but only on ground level. Participants were allowed to pass with both feet. A video showing short passes performed in the Footbonaut can be found in the supplementary material (see Video, Supplemental Digital Content 2, which shows a short section of passes performed in the Footbonaut during preliminary testing, http://links.lww.com/MSS/B860).

Marker trajectories were recorded using 16 infrared cameras operating at 200 Hz (F-40, Vicon, Oxford, UK) mounted above the Footbonaut. The Footbonaut was equipped with ~120 'Torfabrik' (Adidas, Herzogenaurach, GER) soccer balls, which were prepared with six square patches of retro-reflective foil each, so that ball trajectories were visible.

Data processing

Processing of the raw kinematic data was performed in Vicon Nexus 2.3 (Vicon, Oxford, UK). The measurements were cut into single passes containing the whole swing phase. The missing toe-marker trajectories were reconstructed before modelling using MATLAB R2017a (The MathWorks, Natick, Massachusetts, USA). This was done by using the marker coordinates obtained in the standing reference trial, as described in our previous publication (17). Inverse dynamics were performed using AnyBody Modelling System (Version 6.0, AnyBody Technology, Aalborg, DEN). A modified version of the Anatomical Landmark Scaled Model (23) was used. This rigid body model of the lower extremities consists of seven segments with 16 degrees of freedom. Modifications were made at the knee joints, where the original hinge joint was replaced by a ball-socket joint allowing three degrees of freedom. The subtalar and talocrural joints of the ankles were each modelled as adjacent hinge joints. Muscle forces were calculated using the 'AnyMuscleModel' provided in AnyBody with static optimization and a cubic cost function. Previous studies on the validity of the calculated muscle activity have shown good accordance with EMG-measurements (24,25).

Swing phases of ten passes performed with the dominant leg of each subject were randomly selected for further analysis. Start of the swing phase (toe-off) was defined as the MT5-Marker crossing 60 mm above ground level. This height was chosen based on the average height of the MT5-Marker during the standing reference being 50 mm. End of the swing phase was defined as ball contact which was visually obtained for each trial. The ten passes were time-normalized to swing phase and averaged to get the means for each participant, which were then used to calculate group means and perform statistics.

Thigh circumference was taken from the anthropometric measures obtained during testing. Lower limb length was calculated as the sum of shank and thigh length, obtained from the anthropometric measurements taken during the participant preparation. To calculate the segment masses, the shank and thigh segments were regarded as truncated cones from which the volume was calculated using the distal and proximal circumference. These volumes were multiplied with segment densities from Winter (26) to calculate the masses. Lower limb mass is the sum of shank and thigh mass.

Statistics

Statistical analyses were performed in MATLAB 2017a. Each parameter was tested for normality using Shapiro-Wilk-Test. Parameters were then tested for significant main-effects with either the Kruskal-Wallis-Test or an analysis of variance. Independent T-Tests or Wilcoxon-Ranksum-Tests were applied as post-hoc tests where significant main effects were found. The alpha-level for all tests was initially set to 0.05. These were Bonferroni-corrected to 0.0083 ($P^* = 0.05/6$) for the post-hoc tests.

Linear regression analyses were performed to determine the influence of the anthropometric data on the calculated muscle forces. Thigh circumference, thigh mass, lower limb mass, lower limb length and the product of both (length × mass) were used as predictor variables for the muscle forces in adductor longus and gracilis.

RESULTS

Mean values of each parameter in each group and their corresponding standard deviations are presented in Table 2. The peak hip joint angles differed significantly between age groups in the frontal plane but not in the sagittal and transversal planes. U12 had a significantly lower minimum abduction angle compared to U16 (p=0.0034) and U23 (p=0.0007). U15 also had significantly lower minimum abduction angles compared to U16 (p=0.006) and U23 (p=0.0011). The minimum hip abduction angle occurred at toe-off while the maximum hip abduction angle occurred at around 70% of the swing phase on average (Figure 1). Maximum hip abduction angle was significantly different between the U15 and U23 groups (p=0.0069).

Angular velocities at the hip joint were significantly different in the sagittal and frontal plane. Maximum flexion velocity was significantly lower in the U15 group compared to the U12 (p=0.0005) and U16 group (p=0.0025), respectively, and occurred at around 70% of the swing phase (Figure 2). Maximum extension velocity was significantly higher in U16 compared to U23. Maximum adduction velocity was significantly lower in the U15 group compared to the U16 (p=0.0029) and U23 group (p=0.0025). Maximum abduction velocity was significantly higher in the U12 group compared to U15 (p=0.0001), U16 (p=0.0005) and U23 (p<0.0001). In all four groups, the highest abduction velocity occurred at around 50% of the swing phase (Figure 2).

U12 showed significantly lower peak muscle force in adductor longus compared to U15 (p<0.0001), U16 (p<0.0001) and U23 (p<0.0001). U15 also showed significantly lower muscle forces compared to U16 (p=0.0045) and U23 (p=0.0017). Gracilis muscle force was significantly lower in the U12 group compared to U15 (p<0.0001), U16 (p<0.0001) and U23 (p<0.0001). U15 also showed significantly lower muscle forces compared to U16 (p=0.0066) and U23 (p=0.0003) in the gracilis. Maximum forces in both muscles occurred on average at about 70% of the swing phase in all groups (Figure 3), coinciding with the maximum hip abduction (Figure 1).

The linear regression identified lower limb mass as the best predictor (highest R^2) for an increase in calculated muscle force for both investigated muscles (Table 3).

DISCUSSION

The aim of this study was to investigate whether hip joint kinematics and calculated adductor muscle force differ between four age groups during soccer inside passing. Furthermore, the aim was to investigate the influence of lower extremity anthropometrics on the adductor muscle forces. We found that hip adductor muscle forces are different between different age-groups of soccer players, rising across groups from the youngest to the older groups. The highest relative and total increase in muscle force was found between the U12 and U15 teams with a 49% rise in hip adductor muscle force. An increase in lower limb mass was identified as the variable best capable of predicting an increase in hip adductor muscle force.

Previous research has mainly investigated kicking scenarios with a static ball (21,27,28). To the authors' knowledge, the present study is the second to investigate submaximal passing in a dynamic situation. Hip joint angles of the U23 group (Table 2) are in good accordance with joint angles previously reported on submaximal passing in adult soccer players (17). Such an agreement could be expected as the setup of the two studies and the two groups of participants were similar. Despite these similarities, the maximum muscle forces in the present study were slightly lower than in the previous study (17). The lower forces might be a result of a more complex pass protocol used here, where the subjects had to perform passes in all directions, whereas the previous study only investigated passes to the front of the participants. This easier configuration could result in harder passing and therefore higher muscle forces. Furthermore, existing research often reports higher maximum hip angles and angular velocities in all three movement planes (21,28) which is likely due to the investigation of full effort kicking, as compared to submaximal passing in the present study.

The statistical analyses of the passing kinematics revealed only few differences between the four age groups. Those significant differences were concentrated in the frontal plane where most of the movement is executed by the adductor and abductor muscles. While the groups of U23 and U16 showed only a significantly different maximum hip extension velocity compared to each other, there were several significant differences between the U12 and U15 groups in respect to each other but also compared to the two older groups. These differences indicate an alteration of the passing technique between younger and older players. U12 and U15 both experienced less minimum hip abduction, which occurred at toe-off, than the older groups. U15 also showed a lower maximum hip abduction than U23, resulting in an overall reduced range of motion for the U15. However, the U12 group was able to reach a similar maximum abduction angle by increasing their maximum abduction velocity (Table 2 and Figure 2). Without the increase in abduction velocity, the U15 showed a time series of the hip frontal plane angle similar to the older groups but shifted towards a lower degree of abduction by approximately five degrees. They also exhibited a significantly lower maximum adduction velocity compared to the older groups and a significantly lower hip flexion velocity compared to both, the U12 and the U16 groups. The different kinematics could be a result of the U15 group experiencing their growth spurt. The adolescent growth spurt occurs on average at the age of 14 (29) leading to a fast increase in the adolescents segments' length. These fast changes could lead to a loss of coordination and changes in movement strategies which have already been shown for landing tasks in pubescent girls (30). Additionally, this phase has previously been associated with "adolescent awkwardness" which describes a reduction in performance or motor control (29) during puberty.

Furthermore, the longitudinal growth of the bones, during the adolescent growth spurt, occurs prior of the increase in muscle mass (31). This implies an increase in the moments of inertia of the athletes' segments, as the bones grow, which might not be met with sufficient muscle capacity. In passing movements, the highest muscle forces occur close to the end of the back swing (17) when the leg needs to be decelerated using eccentric muscle force. Reducing the abduction velocity reduces the required force to decelerate the leg. Additionally, far joint excursions also require relatively higher muscle force when the movement has to be reversed. As the muscles get stretched further, their ability to produce force decreases. The reduced range of motion and reduced angular velocities that were found in the U15 group might therefore be results of a reduced maximum muscle force and/or a reduced flexibility of the adductor muscles, as a reaction to the increased moments of inertia. Previous studies have found reduced isometric hip adductor strength and reduced hip range of motion to be risk factors for groin injuries (7,32).

The role of the increasing moments of inertia is also important when considering the increase in calculated adductor muscle force (Table 2). A significant increase in force in both investigated muscles was found between the youngest group and each of the older groups. The increase in muscle force was expected, as the participants in the older groups were both heavier and taller, and presumably also stronger. More mass and longer segments lead to higher moments of inertia in the segments, thereby requiring more muscle force to accelerate or decelerate the leg to an equal angular velocity. More considerable is the percentage by which the muscle forces increased between the groups. Between U12 and U15, there was an increase of 49.4% in the gracilis force despite similar adduction velocity. There was also an increase of 22.1% in adductor longus force between U15 and U16 but only 5.6% between U16 and U23. This substantial increase coincides with the adolescent growth spurt that normally occurs around the age of 14 (29). This phase is characterized by the fastest increase of segment length and mass during childhood and adolescence. As written above, this increases the moments of inertia and thereby the demand for higher muscle forces. However, the fast increase in muscle force (and strength) might not be met by a similar fast adaptation of the other musculoskeletal structures. A previous study found an increase in the isometric knee extensor force by ~75% between a group of 10-12 and 13-15 year old boys, while the corresponding cross sectional areas increased by less than 50% between these two groups (33). The increase in muscle force is thought to be accomplished through a better intra-muscular control. This would presumably cause a substantial increase in the stress on the muscle and the tendons, since they would have to withstand the increase in force without an equal increase in cross-sectional area. Tendons have been shown to respond differently to mechanical loading (34), and have been reported to increase their cross sectional area slower than the adjoining muscles during adolescence (35). An imbalance between muscle and tendon growth causes an increase in tendon stress during adolescence (35,36). High tendon stress has been linked to patellar tendinopathy (37). High stress in the tendons of the adductor muscles is therefore a likely risk factor for overuse injuries like tendinopathy and osteitis pubis (38). Overall, these findings suggest, that adolescent players are under an increased injury risk, especially during or shortly after their growth spurt due to the increased moments of inertia. Although there is no data supporting this assumption specifically for groin injuries, a recent study found an increased overall injury incidence for players that were just past their growth spurt (39). This supports the general assumption, that the fast increase in the moments of inertia increases the load on muscles and tendons in general and thereby increases the overall injury incidence.

It is probably of high importance to identify when young athletes experience phases of fast growth in order to prevent the occurrence of overuse injuries since they might be more vulnerable than usually due to the increased tendon stress. For this purpose, lower limb mass could be used as an indicator. In both investigated muscles, lower limb mass was the strongest predictor for the calculated muscle forces. This outcome was not expected, as the moment of inertia is calculated from the squared distance of the center of mass to the rotation center while mass is not squared. However, Table 2 shows that the relative increase in lower limb mass between the age groups (44.8% between U12 and U15) is substantially higher than that of the lower limb length (14.8% between U12 and U15). This more than compensates for the squared influence of the lower limb length in the moment of inertia. Fast increases in lower limb mass could therefore be an indicator of phases with higher susceptibility to injury. Athletes should probably be trained more carefully and sudden increases in training load should be avoided during these growth phases. Using the calculation described in the methods section, lower limb mass can easily be determined by coaches. Additionally, the use of specific adductor strength training like the Copenhagen Adduction Exercise (40) could be used to prepare the adductor muscles for the repetitive loading of submaximal passing.

With the participant sample of this study, no cause and effect can be established between the movement technique and the muscle force to identify movement strategies that might cause higher muscle forces. The effect of the moments of inertia on the increase in muscle force is too dominant between the age groups to find other influences that might increase the muscle forces. Future studies should investigate large homogenous samples to identify movement strategies that increases hip adductor muscle force. The muscle forces were calculated from inverse dynamics analyses and are therefore an estimation of the actual forces based on static optimization. However, a recent study found good accordance between the calculated activity of this model and the measured activity during dynamic movements (25). Although muscle activity and force are not the same, comparing measured to calculated activity is a standard method for model validation (24). The use of retroreflective markers might have influenced the movement of the participants, as this was their first participation in such a measurement. Although such influence cannot be ruled out, it is unlikely that the use of markers influenced the subjects to a degree of unreliability as the markers were both small and light. Additionally, players were familiarized with the markers during warm-up. The cross-sectional design of the present study is only a snapshot of the participants development. Ideally, future studies will use a longitudinal design to investigate year to year effects of maturation on groin injury related parameters.

CONCLUSION

The results of the current study suggest that adolescent soccer players have to cope with the rapid increase of their segments' inertia, inevitably caused by the anthropometric alterations during their growth spurt. This is evident through the reduced angular velocities in the U15 group but also by the high increases in muscle force between the youngest groups. This could suggest an increased risk for overuse injuries among adolescent soccer players. Monitoring the increase of the thigh mass seems to be an easy and applicable method to identify players who could be at increased risk.

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REFERENCES

1. Backous DD, Friedl KE, Smith NJ, Parr TJ, Carpine WD JR. Soccer injuries and their relation to physical maturity. Am J Dis Child 1960. 1988;142(8):839–842.

2. Backx FJ, Erich WB, Kemper AB, Verbeek AL. Sports injuries in school-aged children. An epidemiologic study. Am J Sports Med. 1989;17(2):234–240.

3. Volpi P, Pozzoni R, Galli M. The major traumas in youth football. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2003;11(6):399–402.

4. Shea KG, Pfeiffer R, Wang JH, Curtin M, Apel PJ. Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. J Pediatr Orthop. 2004;24(6):623–628.

5. Lohmander LS, Englund PM, Dahl LL, Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries. Am J Sports Med. 2007;35(10):1756–1769.

6. Wilder FV, Hall BJ, Barrett JP, Lemrow NB. History of acute knee injury and osteoarthritis of the knee: A prospective epidemiological assessment. Osteoarthritis Cartilage. 2002;10(8):611–616.

7. Whittaker JL, Small C, Maffey L, Emery CA. Risk factors for groin injury in sport: an updated systematic review. Br J Sports Med. 2015;49(12):803–809.

8. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. Br J Sports Med. 2011;45(7):553–558.

9. Eckard TG, Padua DA, Dompier TP, Dalton SL, Thorborg K, Kerr ZY. Epidemiology of Hip Flexor and Hip Adductor Strains in National Collegiate Athletic Association Athletes, 2009/2010-2014/2015. Am J Sports Med. 2017;73–80.

10. Gabbe BJ, Bailey M, Cook JL, Makdissi M, Scase E, Ames N, et al. The association between hip and groin injuries in the elite junior football years and injuries sustained during elite senior competition. Br J Sports Med. 2010;44(11):799–802.

11. Hägglund M, Waldén M, Magnusson H, Kristenson K, Bengtsson H, Ekstrand J. Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. Br J Sports Med. 2013;47(12):738–742.

12. Werner J, Hägglund M, Waldén M, Ekstrand J. UEFA injury study: a prospective study of hip and groin injuries in professional football over seven consecutive seasons. Br J Sports Med. 2009;43(13):1036–1040.

13. Mosler AB, Weir A, Eirale C, Farooq A, Thorborg K, Whiteley RJ, et al. Epidemiology of time loss groin injuries in a men's professional football league: a 2-year prospective study of 17 clubs and 606 players. Br J Sports Med. 2018;52:292–7.

14. O'Connor DM. Groin injuries in professional rugby league players: a prospective study. J Sports Sci. 2004;22(7):629–636.

15. Serner A, Tol JL, Jomaah N, Weir A, Whiteley R, Thorborg K, et al. Diagnosis of acute groin injuries: a prospective study of 110 athletes. Am J Sports Med. 2015;43(8):1857–1864.

16. Sailly M, Whiteley R, Read JW, Giuffre B, Johnson A, Hölmich P. Pubic apophysitis: a previously undescribed clinical entity of groin pain in athletes. Br J Sports Med. 2015 Jun;49(12):828–34.

17. Dupré T, Funken J, Müller R, Mortensen KRL, Lysdal FG, Braun M, et al. Does inside passing contribute to the high incidence of groin injuries in soccer? A biomechanical analysis. J Sports Sci. 2018;36(16):1827–1835.

18. Cunningham PM, Brennan D, O'Connell M, MacMahon P, O'Neill P, Eustace S. Patterns of bone and soft-tissue injury at the symphysis pubis in soccer players: observations at MRI. AJR Am J Roentgenol. 2007;188(3):W291-6.

19. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. Br J Sports Med. 2002;36(5):354–359.

20. Vieira LH, Cunha SA, Moraes R, Barbieri FA, Aquino R, Oliveira L de P, et al. Kicking performance in young U9 to U20 soccer players: assessment of velocity and accuracy simultaneously. Res Q Exerc Sport. 2018;89(2):210–220.

21. Katis A, Kellis E. Three-dimensional kinematics and ground reaction forces during the instep and outstep soccer kicks in pubertal players. J Sports Sci. 2010;28(11):1233–1241.

22. Kapidžić A, Huremović T, Biberovic A. Kinematic analysis of the instep kick in youth soccer players. J Hum Kinet. 2014;42:81–90.

23. Lund ME, Andersen MS, de Zee M, Rasmussen J. Scaling of musculoskeletal models from static and dynamic trials. Int Biomech. 2015;2(1):1–11.

24. Alexander N, Schwameder H. Comparison of Estimated and Measured Muscle Activity During Inclined Walking. J Appl Biomech. 2016;32(2):150–159.

25. Dupré T, Dietzsch M, Komnik I, Potthast W, David S. Agreement of measured and calculated muscle activity during highly dynamic movements modelled with a spherical knee joint. J Biomech. 2019;84:73–80.

26. Winter DA. Biomechanics and motor control of human movement. 4th ed. Hoboken: John Wiley & Sons; 2009.

27. Nunome H, Asai T, Ikegami Y, Sakurai S. Three-dimensional kinetic analysis of side-foot and instep soccer kicks. Med Sci Sports Exerc. 2002;34(12):2028–2036.

28. Levanon J, Dapena J. Comparison of the kinematics of the full-instep and pass kicks in soccer. Med Sci Sports Exerc. 1998;30(6):917–927.

29. Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, et al. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci. 2006;24(3):221–230.

30. Wild CY, Munro BJ, Steele JR. How Young Girls Change Their Landing Technique Throughout the Adolescent Growth Spurt. Am J Sports Med. 2016 May;44(5):1116–23.

31. Malina RM. Adolescent changes in size, build, composition and performance. Hum Biol. 1974 Feb;46(1):117–31.

32. Tak I, Engelaar L, Gouttebarge V, Barendrecht M, Van den Heuvel S, Kerkhoffs G, et al. Is lower hip range of motion a risk factor for groin pain in athletes? A systematic review with clinical applications. Br J Sports Med. 2017;51(22):1611–21.

33. Kanehisa H, Ikegawa S, Tsunoda N, Fukunaga T. Strength and cross-sectional areas of reciprocal muscle groups in the upper arm and thigh during adolescence. Int J Sports Med. 1995 Jan;16(1):54–60.

34. Heinemeier KM, Bjerrum SS, Schjerling P, Kjaer M. Expression of extracellular matrix components and related growth factors in human tendon and muscle after acute exercise. Scand J Med Sci Sports. 2013;23(3):e150–61.

35. Mersmann F, Bohm S, Schroll A, Boeth H, Duda G, Arampatzis A. Evidence of imbalanced adaptation between muscle and tendon in adolescent athletes. Scand J Med Sci Sports. 2014;24(4):e283–9.

36. Waugh CM, Blazevich AJ, Fath F, Korff T. Age-related changes in mechanical properties of the Achilles tendon. J Anat. 2012;220(2):144–155.

37. Couppé C, Kongsgaard M, Aagaard P, Vinther A, Boesen M, Kjaer M, et al. Differences in tendon properties in elite badminton players with or without patellar tendinopathy. Scand J Med Sci Sports. 2013 Mar;23(2):e89-95.

38. Hiti CJ, Stevens KJ, Jamati MK, Garza D, Matheson GO. Athletic osteitis pubis. Sports Med. 2011;41(5):361–376.

39. Bult HJ, Barendrecht M, Tak IJR. Injury Risk and Injury Burden Are Related to Age Group and Peak Height Velocity Among Talented Male Youth Soccer Players. Orthop J Sports Med. 2018 Dec;6(12):1–10.

40. Harøy J, Thorborg K, Serner A, Bjørkheim A, Rolstad LE, Hölmich P, et al. Including the Copenhagen Adduction Exercise in the FIFA 11+ Provides Missing Eccentric Hip Adduction Strength Effect in Male Soccer Players: A Randomized Controlled Trial. Am J Sports Med. 2017 Nov;45(13):3052–9.

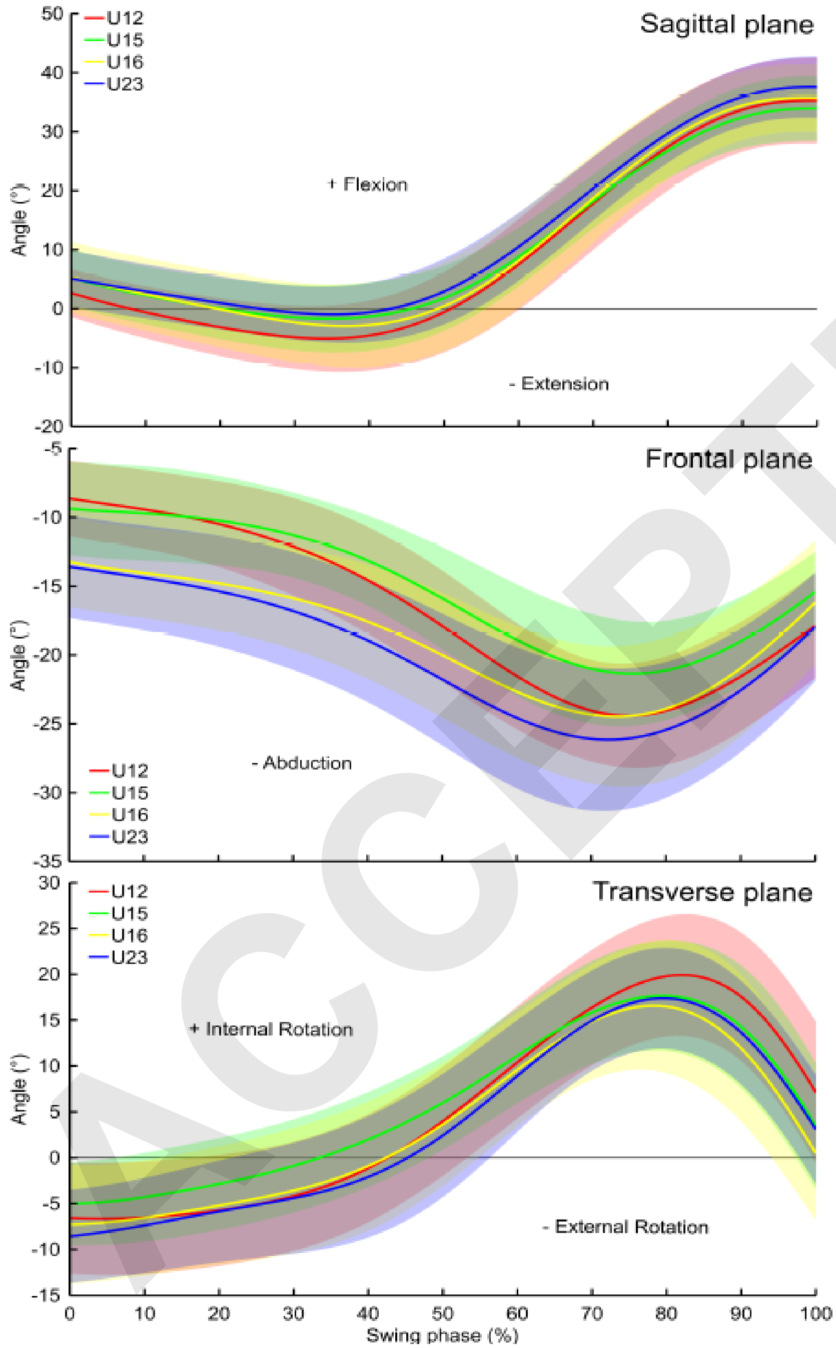
FIGURE CAPTIONS

Figure 1: Represented are the time series of the hip joint angles as mean values for each of the four age groups. Every subfigure shows one plane of movement. Shaded areas indicate ± one standard deviation. Data is presented time-normalized between toe-off (0%) and ball contact (100%).

Figure 2: Represented are the time series of the hip joint angular velocities as mean values for each of the four age groups. Every subfigure shows one plane of movement. Shaded areas indicate ± one standard deviation. Data is presented time-normalized between toe-off (0%) and ball contact (100%).

Figure 3: Represented are the time series of the muscle force in the adductor longus and gracilis as mean values for each of the four age groups. Shaded areas indicate ± one standard deviation. Data is presented time-normalized between toe-off (0%) and ball contact (100%).

Figure 1



Sagittal plane
U12
U15
U16
U23
+ Flexion
- Extension
Angle (°)
50
40
30
20
10
0
-10
-20
Frontal plane
- Abduction
-5
-10
-15
-20
-25
-30
-35
Transverse plane
+ Internal Rotation
- External Rotation
30
25
20
15
10
5
0
-5
-10
-15
0
10
20
30
40
50
60
70
80
90
100
Swing phase (%)

Figure 2

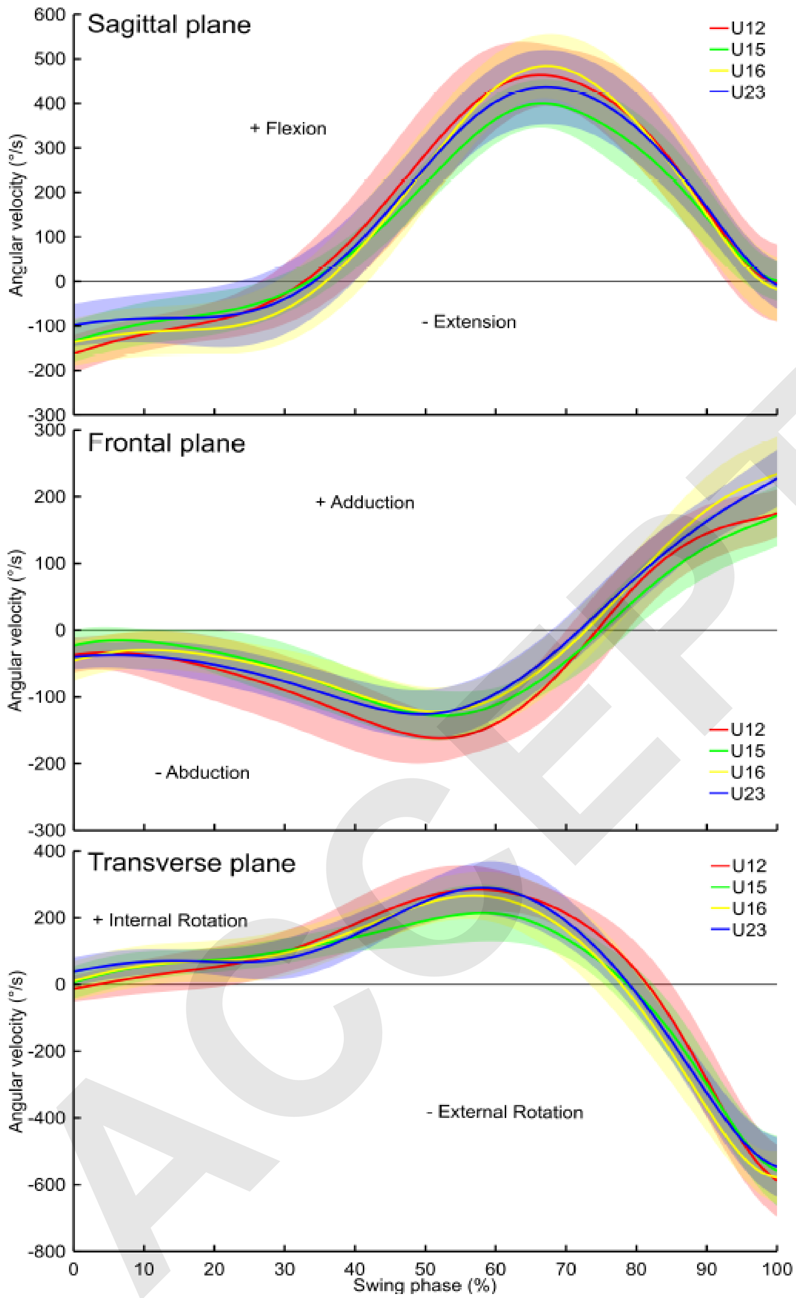
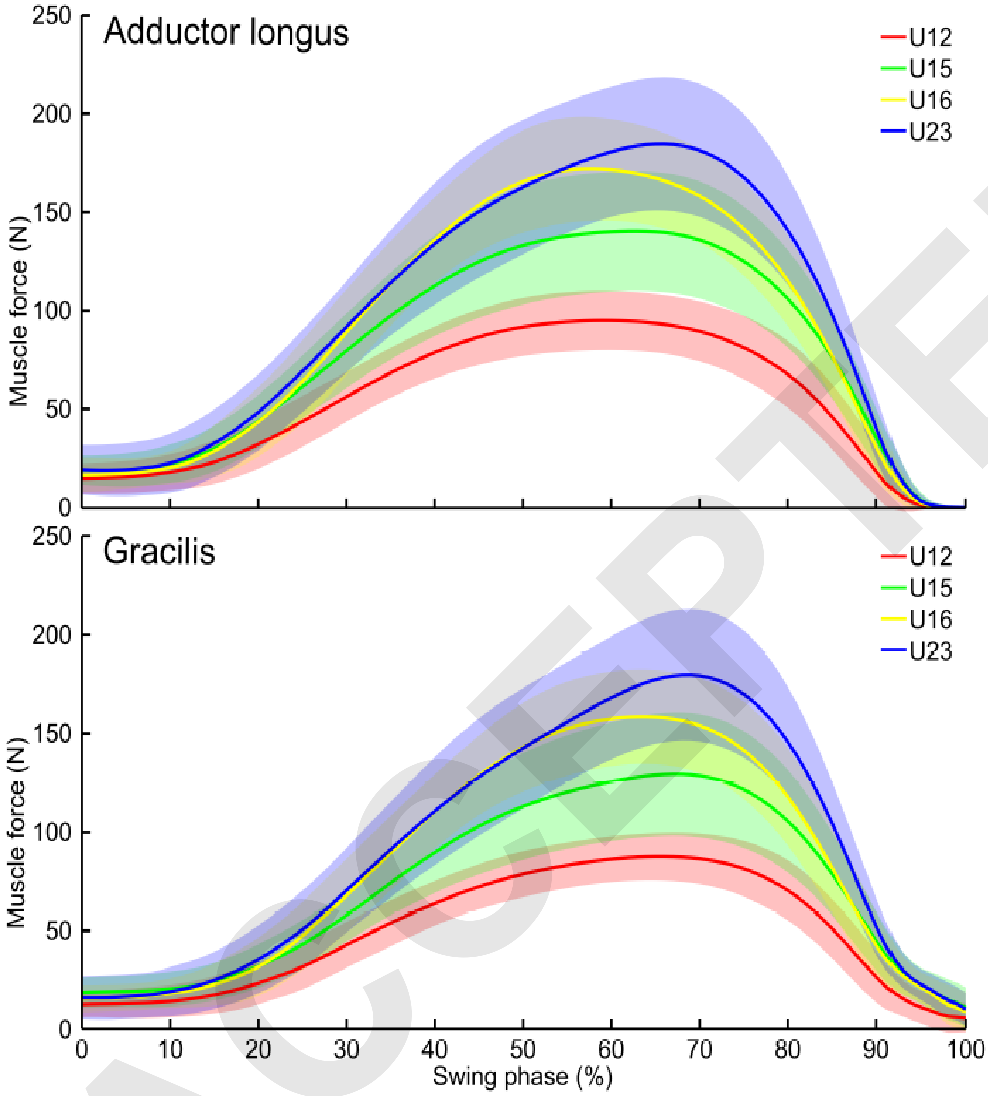

Sagittal plane
U12
U15
U16
U23
+ Flexion
- Extension
Angular velocity (°/s)
600
500
400
300
200
100
0
-100
-200
-300
Frontal plane
+ Adduction
- Abduction
Angular velocity (°/s)
300
200
100
0
-100
-200
-300
U12
U15
U16
U23
Transverse plane
+ Internal Rotation
- External Rotation
Angular velocity (°/s)
400
200
0
-200
-400
-600
-800
U12
U15
U16
U23
0
10
20
30
40
50
60
70
80
90
100
Swing phase (%)

Figure 3



Adductor longus
U12
U15
U16
U23
Muscle force (N)
250
200
150
100
50
0
Gracilis
U12
U15
U16
U23
Muscle force (N)
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Swing phase (%)

Table 1: Distribution and characteristics (Mean ± standard deviation) of the anthropometric data for the four groups of players.

Group	N	Age (a)	Height (cm)	Mass (kg)
U12	14	11.1 ± 0.5	149.7 ± 7.8	38.3 ± 4.8
U15	17	14.7 ± 0.4	171.8 ± 7.6	60 ± 9.6
U16	14	15.8 ± 0.2	172.1 ±7.8	64.8 ± 8.6
U23	15	20.2 ± 0.9	179.2 ± 8.7	75 ± 7.8

Table 2: Means and standard deviations of the four different groups for the maximum hip joint angles, angular velocities and muscle forces. Data was calculated from ten shots of each participant between toe-off and ball contact. * indicates significant difference to the mean of U15, † indicates significant difference to the mean of U16, ‡ indicates significant difference to the mean of U23. The bottom section shows the measured and calculated anthropometrics of the four groups without indications of statistical differences.

	U12	**U15**	**U16**	**U23**
		Hip angles (°)		
Flexion	36.12 ± 7.42	34.62 ± 5.52	36.46 ± 5.77	38.06 ± 5.29
Extension	6.76 ± 5.49	3.08 ± 5.37	4.99 ± 6.96	2.75 ± 4.52
Min. abduction	7.5 ± 3.14 †‡	7.88 ± 3.28 †‡	11.34 ± 3.17	12.21 ± 3.5
Max. abduction	25.27 ± 4.03	22.06 ± 3.81 ‡	25.25 ± 5.3	26.79 ± 5.38
Internal rotation	21.05 ± 7.03	19.15 ± 6.07	17.76 ± 7.5	18.01 ± 5.79
External rotation	8.59 ± 6.12	7.46 ± 4.83	9.74 ± 6.22	9.37 ± 5.57
		Hip angular velocities (°/s)		
Flexion	530.84 ± 69.3 *	439.18 ± 61.26 †	526.56 ± 85.64	485.07 ± 81.82
Extension	196.01 ± 36.63	170.5 ± 33.67	208.97 ± 46.41 ‡	154.76 ± 51.85
Adduction	187.85 ± 38.6	179.02 ± 44.77 †‡	238.61 ± 57.46	230.46 ± 43.3
Abduction	204.11 ± 22.89 *†‡	158.1 ± 32.36	156.69 ± 37.93	151.09 ± 28.56
Internal rotation	335.65 ± 61.25	282.13 ± 61.52	323.89 ± 71.58	331.39 ± 74.49
External rotation	598.2 ± 110.95	556.94 ± 106.97	590.21 ± 77.28	552.14 ± 88.82
		Muscle forces (N)		
Adductor Longus	101.3 ± 16.03 *†‡	150.19 ± 29.76 †‡	183.38 ± 27.59	193.71 ± 37.3
Gracilis	92.37 ± 13.45 *†‡	137.98 ± 30.18 †‡	167.5 ± 24.91	185.9 ± 36.66
		Anthropometrics		
Thigh circumference (cm)	43.46 ± 3.46	51.45 ± 5.17	54.31 ± 3.29	57.98 ± 2.6
Thigh mass (kg)	4.41 ± 0.67	6.34 ± 1.03	6.82 ± 0.84	7.82 ± 1.05
Lower limb length (cm)	70.26 ± 4.07	80.64 ± 4.67	78.9 ± 4.37	83.48 ± 5.46
Lower limb mass (kg)	6.36 ± 0.98	9.21 ± 1.43	9.89 ± 1.29	11.18 ± 1.44
Lower limb mass × lower limb length (kg × cm)	450.06 ± 92.26	745.46 ± 139.59	784.25 ± 138.92	939.49 ± 179.26

Table 3: Results of the linear regression analysis using the anthropometric parameters as predictive variables for the calculated muscle forces.

Response Variable	Predictor	R^2	p-value
Adductor longus muscle force	Thigh circumference	.618	< 0.001
	Thigh mass	.653	< 0.001
	Lower limb mass	.696	< 0.001
	Lower limb length	.507	< 0.001
	Lower limb mass × Lower limb length	.675	< 0.001
Gracilis muscle force	Thigh circumference	.647	< 0.001
	Thigh mass	.694	< 0.001
	Lower limb mass	.734	< 0.001
	Lower limb length	.535	< 0.001
	Lower limb mass × Lower limb length	.719	< 0.001

Supplemental digital content 1: Overview of the anthropometric measurements. Except for body mass (measured in kg), measurements were taken in meters.

Category	Parameter	Description	Method
General	Body height	Absolute body height	Ruler
	Body mass	Absolute body mass	Scale
Heights	Height of the medial malleolus	Ground to malleolus	Tape measure
	Height of the medial knee epicondyle	Ground to epicondyle	Tape measure
	Functional leg length	Ground to bottom of the pelvis	Spirit level + tape measure
	Waist height	Ground to smallest point of trunk	Ruler
	Height of the xiphoideus	Ground to xiphoideus	Ruler
	Height of suprasternal notch	Ground to suprasternal notch	Ruler
	Height of C7 vertebra	Ground to C7	Ruler
	Height of C1 vertebra	Ground to C1	Ruler
Length, width and thickness	Absolute hip width	Distance between the two trochanters	Anthropometric caliper
	Hip joint width	Distance between the joint centers	Anthropometric caliper
	Waist width	Smallest circumference of the trunk	Anthropometric caliper
	Thorax width	Measured at the height of the xiphodieus	Anthropometric caliper
	Thorax depth	Measured at the height of the xiphodieus	Anthropometric caliper
	Shoulder width	Wrist to tip of third finger	Anthropometric caliper
	Hand length	Wrist to tip of third finger	Anthropometric caliper
	Hand width	Widest point of the flat hand	Anthropometric caliper
	Hand thickness	Measured in the middle of the hand	Anthropometric caliper
	Foot length	Heel to tip of first toe	Anthropometric caliper
	Foot width	Widest point of the foot	Anthropometric caliper
	Biggest head height	Measured from chin to top of the head	Anthropometric caliper
	Head breadth	Temple to temple	Anthropometric caliper
	Head depth	Forehead to back of the head	Anthropometric caliper
	Smallest head height	Measured from C1 vertebra to top of the head	Anthropometric caliper
	Trunk height	Measured as C7 to L5 along the trunk	Tape measure
	Thigh length	Trochanter to lateral femur epicondyle	Tape measure
	Shank length	Lateral knee epicondyle to lateral malleolus	Tape measure
	Upper arm length	Shoulder joint to lateral humerus epicondyle	Tape measure
	Lower arm length	Lateral humerus epicondyle to wrist	Tape measure
Circumference	Thigh circumference	Measured at the widest point of the thigh	Tape measure
	Biggest shank circumference	Measured at the widest point of the shank	Tape measure
	Smallest shank circumference	Measured at the thinnest point of the shank	Tape measure
	Biggest upper arm circumference	Measured at the widest point of the upper arm	Tape measure
	Biggest lower arm circumference	Measured at the widest point of the lower arm	Tape measure
	Smallest lower arm circumference	Measured at the wrist	Tape measure
	Hip circumference	Measured at the height of the trochanters	Tape measure
	Waist circumference	Measured smallest point of the trunk	Tape measure
	Thorax circumference	Measured at the height of the xiphoideus	Tape measure
	Neck circumference	Measured around the neck	Tape measure
Calculated	Pelvis Height	C7 height - (functional leg length + trunk height)	Calculated