Fall 1-8-2021

Kinematics, Kinetics, and Modeling of Fatigue in Young Distance Runners

Susan Basile
Georgia State University

ACCEPTANCE

This dissertation, KINEMATICS, KINETICS, AND MODELING OF FATIGUE IN FEMALE YOUTH DISTANCE RUNNERS by SUSAN BASILE, was prepared under the direction of the candidate's Dissertation Advisory Committee. It is accepted by the committee members in partial fulfillment of the requirements for the degree, Doctor of Philosophy, in the College of Education & Human Development, Georgia State University.

The Dissertation Advisory Committee and the student's Department Chairperson, as representatives of the faculty, certify that this dissertation has met all standards of excellence and scholarship as determined by the faculty.

____
Jianhua Wu, PhD
Committee Chair

____
Mark Geil, PhD
Committee Member

____
Feng Yang, PhD
Committee Member

____
Sujay Galen, PhD
Committee Member

____
Date

____
Jacalyn Lund, PhD
Chairperson, Department of Kinesiology and Health

____
Paul Alberto, PhD
Dean, College of Education &
Human Development

AUTHOR'S STATEMENT

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Susan Ann Basile
Kinesiology
College of Education & Human Development
Georgia State University

The director of this dissertation is:

Jianhua Wu, PhD
Department of Kinesiology and Health
College of Education & Human Development
Georgia State University
Atlanta, GA 30303

CURRICULUM VITAE

SUSAN BASILE

347-249-3629

sue.basile@gmail.com

sbasile2@student.gsu.edu

I. Education

Georgia State University, Atlanta, GA
PhD, Kinesiology, Biomechanics Specialization 2013 – present
Dissertation: "Kinematics And Modeling Of Fatigue In Youth Distance Runners"
Defended: July 2020

University of Tennessee, Knoxville, TN
MS, Dept. of Mechanical, Aero, and Biomedical Engineering, Concentration in Biomechanics 2007 - 2009
Thesis: "Modeling and Analysis of Proximal Tibial Growth Plate Fractures in Adolescents"

Columbia University, New York, NY
BS, Biomedical Engineering, Biomechanics track; minor in Economics 2003 – 2007

II. Research Experience

Georgia State University (2013 – present)

Completed collaborative research project on the variability and calculation of knee joint centers. This project utilized a Vicon 3D camera system and data analysis software to estimate and manually calculate the knee joint centers for multiple types and manufacturers of prosthetic knee.

Conducted international collaborative research in New Zealand as a recipient of the National Science Foundation East Asia and Pacific Summer Institute Fellowship. The associated project investigated the effects of fatigue on the kinetics and kinematics of adolescent distance runners.

Part of a group attempting to quantitatively define vaulting for standard use across disciplines using knee brace immobilization.

University of Tennessee (2007 – 2009)

Completed a masters research project that simulated and analyzed forces at the proximal knee and visualized areas of increased stress and strain. Employed dynamometer force data in conjunction with finite element analysis software to calculate the forces and stresses acting on the knee of adolescents, a unique population vulnerable to conditions such as tibial avulsion and Osgood-Schlatter's disease.

III. Awards and Appointments

American Society of Biomechanics Travel Award	2016
NSF EAPSI Research Fellow	2015
Georgia State University Dean's Fellow	2013 – 2017
University of Tennessee Graduate Pipeline Fellow	2007 – 2009
Columbia University C.P. Davis Scholar	2003 – 2007
Reviewer: *Medical & Biological Engineering & Computing*	2013 – present
Reviewer: *Columbia Undergraduate Science Journal*	2002 – 2003

Member: *International Society of Biomechanics* 2014 – present
Member: *American College of Sports Medicine* 2013 – present

IV. Presentations & Publications

Lead Author: "Modeling and Analysis of Proximal Tibial Growth Plate Fractures in Adolescents: Theory and Potential Applications", *Advances in Pediatric Research*

Basile, Susan, Oliver, John, Geil, Mark. "Effect Of Fatigue On Kinematic And Kinetics Of Youth Runners: A Pilot Study," International Society of Sports Biomechanics Annual Conference, Cologne, Germany, June 2017

Basile, Susan, Oliver, John. "Pilot Study on the Effect of Fatigue on the Kinetics and Kinematics of Youth Runners". American Society of Biomechanics Annual Conference, Raleigh, NC, August 2016

Geil, M.D., Gharai, M.H., Basile, S, "Prosthetic Knee Joint Center of Rotation Error in Gait Analysis," American Academy of Orthotists and Prosthetists Annual Meeting and Symposium, New Orleans, LA, February 2015

Basile, Susan, Xiaopeng Zhao, "Modelling and Analysis of Proximal Tibial Growth Plate Fractures in Adolescents," Oak Ridge National Laboratory Biomedical Science and Engineering Conference, Knoxville, Tennessee, March 2009

Basile, Susan, Xiaopeng Zhao, Mingjun Zhang, "Dynamics and Control of Electroporation," ASME International Mechanical Engineering Congress and Exposition, Boston, Massachusetts. November 2008

V. Teaching and Leadership Activities

Brooklyn College, City University of New York
Adjunct Assistant Professor

Methods Of Evaluation (KINS 3060) – Spring 2019, Fall 2019, Spring 2020
Biomechanics (KINS 4250) – Spring 2019, Fall 2019, Spring 2020
Graduate Biomechanics (KINS 7263) – Spring 2019, Spring 2020

Georgia State University
Lecturer, *Advanced Biomechanics (KH4600),* Spring 2016

Teaching Assistant and Lab Instructor, *Undergraduate Biomechanics (KH3600),* Fall 2014, Fall 2015

Georgia State Latino Student Services Mentor, 2014 – 2018

Part of an outreach program in the Office of Latino Student Services that provides undergraduate and first-generation Latino students with academic support services as well as advice on personal and professional development.

Massachusetts Institute of Technology OEOP Mentor, 2013 - present

Active alumni of MITES program aimed at diversifying the science and engineering community by reaching out to students from underrepresented backgrounds and enabling these students to develop the skills and confidence needed to pursue careers in STEM fields.

KINEMATICS, KINETICS, AND MODELLING OF FATIGUE IN FEMALE YOUTH DISTANCE RUNNERS

by

SUSAN BASILE

Under the Direction of Dr. Jianhua Wu

ABSTRACT

Running has always been a popular hobby and exercise activity, in part because of its low participation barriers. In recent years, organized distance races have reported increases in children and young adult participants, with some even running full marathons. In addition, high school level cross country participation is increasing in a number of areas. This increased participation warrants particular attention in female athletes due to generally higher rates of injury, including those due to overuse and specialization. These early injuries can lead to higher likelihood of future injuries, growth plate disruption, and more psychological outcomes like burnout However, there is no general consensus among coaches, physicians, or athletic bodies about safe cumulative running loads at younger ages. There has and continues to be a great deal of research regarding running injuries and their etiologies in adults, considering, among other aspects, ground reaction forces, loading rates, and various kinematic factors. There is much less centered on running injuries in children that are not within the context of another sport (particularly soccer), and there is little data on how fatigue affects younger runners specifically. If there is a difference in how younger runners handle fatigue, then it is possible to address the issue through training strategies, and/or to encourage limits on distance or running volume, similar to the pitching limits enacted in youth baseball. The purpose of this study was to investigate how kinematics, kinetics, and muscle activations changed with fatigue in a group of young female distance runners. Eleven healthy girls aged 8-17 years participated in this study. Motion and ground reaction force data were collected before and after a 5-kilometer run at or near the subjects' personal best pace. The resultant data was processed and characteristics such as joint angles, ground reaction forces, and cadence were compared via for pre and post run, as well as for the younger runners compared to the older runners. The data collected was also employed in a modeling simulation and static optimization to investigate changes in muscle forces. Results showed that the ankle joint mechanics were most significantly altered by fatigue, and that knee kinetics were most affected with fatigue by the runners' age, potentially because of compensation for weaker knee strength typically exhibited by physically immature athletes. In addition, knee flexor forces increased and extensor forces decreased with fatigue, while changes to muscle forces around the hip and ankle were more dependent on the age of the runner, with younger runners at greater risk for injuries such as iliotibial band syndrome and stress fractures. These results suggest that performance and potentially injury avoidance in these young runners can be aided by strengthening the involved muscles to avoid imbalances, as well potentially limiting the running volume of younger runners.

INDEX WORDS: Biomechanics; Modelling; OpenSim; Running; Youth Sports; Overuse

KINEMATICS, KINETICS, AND MODELLING OF FATIGUE IN FEMALE YOUTH DISTANCE RUNNERS

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SUSAN BASILE

A Dissertation

Presented in Partial Fulfillment of Requirements for the

Degree of

Doctor of Philosophy

in

Biomechanics

in

Kinesiology

in

the College of Education & Human Development
Georgia State University

Atlanta, GA
2020

ACKNOWLEDGMENTS

I would like to express deep appreciation for all of my committee members. For Drs. Wu and Geil, for being incredibly understanding and patient through this long dissertation process, for always being tremendous sources of knowledge and encouragement, and for fostering a supportive and collaborative lab atmosphere. Thank you Drs. Galen and Yang – I am incredibly grateful that you were able to step in and help in the completion of this part of my academic journey. I would like to thank my lab mates, who both kept my spirits up and directly supported this work. Above all I would like to thank my parents, family, and friends for their constant support across all aspects of my life, which I wouldn't have made it to this point without.

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1. Guiding Questions

There is a concern over a growing bifurcation as it relates to children and adolescents and physical activity. The rates of obesity in children and young adults have increased by approximately five and seven percent respectively for girls and boys over the last forty years (Abarca-Gómez et al. 2017). Conversely, an increasing number of children are specializing in a sport. While the specific definition of specialization may vary slightly depending on the context, it is generally understood to be when an athlete chooses to play one sport nearly or all-year-round, and to the exclusion of other sports and activities. Studies have placed the number of specialized athletes participating in high school sports to be everywhere from 13.4% to 41.1%, and this group has been found to be at greater risk for injuries overall, but more so for overuse injuries, particularly ones that require more than a month's worth of recovery. (Bell et al. 2016; Post et al. 2017; Pasulka et al. 2017; McGuine et al. 2017; Moseid et al. 2019). Girls tend to experience higher rates of overuse injuries, more often coming in individual sports like tennis and gymnastics. Some surveillance studies have track and field as the highest injury risk for young women, with an injury rate of 3.82 per 10,000 athletic exposures, with nearly 37% of all injuries in the sport being overuse injuries (Schroeder et al. 2015).

Among the most prevalent concerns regarding specialization is burnout – both psychological and physical, leading to cessation of participation in what was originally a loved sport. The later type of burnout can often manifest in overuse injuries, which can be influenced by fatigue and the volume and repetition of homogeneous movement that comes with playing a single sport so consistently. In addition, adolescent athletes are still in the early stages of fine-tuning their biomechanics and neuromuscular control, which can also be exacerbated by fatigue. Research has demonstrated a higher incidence of both lower extremity and overuse injuries at increased levels of specialization (Bell et al. 2016; Pasulka et al. 2017; McGuine et al. 2017; Moseid et al. 2019). Overuse injuries can be particularly harmful if they result in physeal plate injuries, which in turn can lead to limb-length discrepancies and earlier onset of conditions such as osteoarthritis. Given the potential for long-term harm, there has been much discussion about limiting the volume and/or frequency of activity in younger athletes. Little League Baseball, for example, has developed regulations about how many pitches and how often a player can throw, and the specific rules vary with age. Tennis has also limited exposure to younger players, introducing age eligibility rules that allowed players between 14 and 18 to gradually increase the quantity and level of play, based on their age and performance. Ten years after the introduction found that the average length of a career as well as the odds of having a 10+ year career increased, even accounting for changes in areas like sports medicine and nutrition (Otis et al. 2006).

Running is a popular sport and an accessible leisure activity that is low in cost, and has numerous physiological benefits, including cardiovascular fitness, bone strengthening, and prevention of diseases like diabetes (Jenny & Armstrong 2013). Youth participation in activities like distance running and triathlons has been steadily increasing, with children running longer distances at earlier ages. In 2013, at least 70,000 children between six and seventeen participated in a half or full marathon (Running USA’s Annual Marathon Report | Running USA). A survey of state cross country and track and field associations conducted by The National Federation of High School Associations ranks participation in cross country 5th most popular among all possible sports, and 4th among girls, with 472,597 and 221,616 athletes respectively (The National Federation Of State High School Associations 2015). There is also anecdotal evidence of middle and high school runners attempting full triathlons and even ultra-marathons – any race longer than 26.2 miles – distances. Given that all of these numbers are potentially an underestimate, as they only account for official statistics and specific organizations, this represents a significant at-risk population. However, there is no current consensus on what safe levels of volume at these developmental stages are. There is increasing awareness that existing biomechanics research revolving around adults cannot simply be 'scaled down' and directly applied to children and adolescents, leading to an increased emphasis on conducting relevant studies on this population. However, most current investigations of the running biomechanics of youth are centered on sprinting and sports that happen to involve running, such as soccer (Mercer et al. 2010; Rozumalski et al. 2015; Rumpf et al. 2015).

Valid research also has to take into account not only differences between the sexes, but variety between pubertal stages, as material properties of biological tissues change throughout the growth period. For example, the stiffness of tendons, including the patellar and Achilles tendons, increase during maturation (Meng & Untaroiu 2018). There is also evidence that kinematic and kinetic differences between boys and girls for dynamics movements like jumping and cutting widen some time during or shortly after puberty (Hewett et al. 2004; Quatman et al. 2006). Combined with rapid growth and changes in muscular strength, it is important to determine how these characteristics influence injury risk in young runners.

The purpose of this dissertation project was to examine the kinematics, kinetics, and muscle activations of female youth runners and how fatigue affects these biomechanical patterns. The results will hopefully begin to highlight differences between young and adult runners, particularly young female runners, who tend to be understudied as a group, and who generally report more overuse-type injuries due to specialization than their male counterparts (Jayanthi et al. 2020). Based on the degree of observed differences, the results can be used for future guidelines on volume limits for younger runners, or used for mechanics corrections and/or strength training if the risk factors are modifiable.

2. Literature Review

2.1 Running biomechanics in adults and children

Potential injury risk predictors for long distance runners are well studied in the adult population and include leg acceleration, knee and leg stiffness and step length and rate. While individuals with a history of tibial stress fractures were shown to have higher values of knee stiffness, lower knee stiffness has been associated with soft tissue injuries (Wen et al. 1997; J. Mizrahi et al. 2000; Milner et al. 2006; Wen 2007; Pohl et al. 2008; Edwards et al. 2009; Heiderscheit et al. 2011).

In a female-specific study, fatigue induced by an exhaustive treadmill run resulted in decreased impact peak by an average of 6.6% and loading rates by 11.8% (van der Worp et al. 2015). The changes in ground reaction forces were attributed to a decrease in cadence, increase in step length, and altered lower joint kinematics. These results could be viewed either as an active response by the runners to lessen impact forces as a protective function by employing soft tissue and muscles and absorb impact, or as simply a fatigue-induced deviation from optimal biomechanics. Runners who had been injured in the previous year also experienced higher impact peaks and loading rates (Gerlach et al. 2005), evidence to support the latter explanation. Through retrospective study (Milner et al. 2006), peak hip adduction, peak rearfoot eversion, and absolute free moment, defined as the torque about a vertical axis resulting from the friction between the foot and the ground during stance phase, have been shown to be the best predictors of tibial stress fractures in female runners.

In a comparison between the 1st and to the 30th minute of running on a treadmill, runners' average stride rate decreased, maximal knee extension increased, and average impact acceleration on the shank - measured via accelerometer - increased by approximately 4 times gravitational acceleration. (Joseph Mizrahi et al. 2000). Decreased muscle activation is given as one potential factor for the increase in impact acceleration. Additionally, EMG indicated that in the fatigued state, activity of the gastrocnemius increased, while that of the tibialis anterior decreased. This is an important finding due to the role of the lower limb muscles during gait as shock absorbers in stabilizing the leg at and after heel strike. Also, imbalances in strength or in fatigue rates in the shank muscles can increase the bending and/or tension forces placed on the tibia, predisposing the athlete to an overuse injury. The changes in kinematics between novice and competitive runners as they fatigue were investigated as 15 of each group ran at 3.2km trial pace. The novice runners changed their kinematics to a larger degree, particularly their trunk lean and hip abduction (Maas, Bie, et al. 2018). Since the subjects in this study are training regularly, the degree to which their kinematics change should fall closer to that of the competitive runners as opposed to the novice ones.

The physiological differences between youth and adult athletes are becoming increasingly well studied. For example, pre and early adolescents have not yet developed the anaerobic power or localized muscular strength necessary for events that involve more explosivity such as sprinting, jumping, and throwing, nor do they acclimate to extreme conditions like heat as readily. However, they are able to recover from such efforts more quickly than adults (Bar-Or 1995, p.). Boys, even at the late stages of adolescence, showed less fast-twitch b fiber hypertrophy than adults under a 3-month training program (Fournier et al. 1982). Levels of muscular co-contraction also change with maturity. EMG were collected at the end of a 4-minute treadmill exercise bout in a mixed group of seven to sixteen-year-olds for their vastus lateralis, hamstrings, tibialis anterior, and soleus muscles. Co-contraction 1) decreased with age and 2) the differences between age groups increased with speed. This co-contraction can be an indicator that the motor skills of the younger group are still underdeveloped, or that these muscles are counteracting a greater instability (Frost et al. 1997). Either case results in a higher metabolic cost and has implications for younger children running long distances. Simulating different levels of co-contraction of the leg muscles in OpenSim can provide insights into how this may change things like joint forces and moments. A potentially confounding factor in maturational studies like this is that the children were grouped solely according to age; when subjects include both boys and girls, the girls in the 15-16 range may be two or even three years removed from their peak height velocity (PHV), and the boys in the 10-12 group may still be five or more years away from theirs. It was also not specified whether or not the children were runners.

There is no current consensus on acceptable levels of running volume by age – either in terms of a single running bout or weekly/monthly accumulated mileage. Advocates of allowing children to run marathon-distance events have relied on reported injury data from marathons (Roberts 2007). However, such reports can only capture injuries that happen during the course of a marathon and are not accounting for the mileage before the race, nor the potential overuse or other related injuries that may occur in the longer term. Conversely, professionals such as the International Marathon Medical Directors Association have issued statements suggesting that marathons shouldn't be undertaken until a runner's eighteenth birthday (Rice et al. 2003). Between 1994 and 2007 a total of 225,344 children were treated in ERs for running-related injuries. The annual incidence was also found to be steadily increasing throughout the observational period, with those between the ages of 12 and 14 having the highest injury rate at 45.8 per 100,000 (Mehl et al. 2011). In addition, the younger children were more likely to have traumatic injuries and fractures, with older children and adolescents, experiencing more overuse injuries.

A retrospective study of a random cross section of 5-17 year-old patients at a Boston Children's sports medicine clinic also found similar injury differences between the younger (five to 12 year-olds) and older (13 and over) children. Again, the younger children came in with more fractures and traumatic-type injuries, including physeal fractures, apophysitis, and osteochondritis dissecans. The adolescents were more likely to have overuse and soft tissue injuries, including meniscal tears, and spondylolysis (Stracciolini et al. 2013). This group also looked specifically at the differences in sports injuries between the population's boys and girls. The girls were found much more likely to develop an overuse and/or soft tissue-related injury, whereas the boys were slightly more likely to experience a traumatic or bone-related injury. The girls also experienced three times as much patellofemoral knee pain, while osteochondritis dissecans was more common in boys. Both experienced similar rates of ACL injuries (Stracciolini et al. 2014). Given the combination of these two studies, it seems that males under 13 are at increased risk of developing osteochondritis dissecans, and adolescent female athletes are at the highest risk of developing an overuse injury. Changes in muscular strength between the sexes also varies – before puberty, boys and girls gain upper and lower body strength in relationship to changes in height, while boys strength continues to increase even after the pubertal phase (Parker et al. 1990).

A longitudinal study focused on the implications of specialization as it affects the kinematics of the knee in female athletes matched 79 adolescent girls that played multiple sports with one that specialized in one of either basketball, soccer, or volleyball (DiCesare et al. 2019). Athletes were also designated as pre, mid, or post-pubertal and completed a drop vertical jump task on two lab visits at least six months apart. Small or non-existent variations in knee kinematics between the specialized and non-specialized athletes before puberty became significant post-puberty. This included greater peak knee abduction angle and moment, and to a lesser degree the knee extensor moment. These biomechanics could elevate the risk of issues like ACL injury and patellofemoral pain. In addition, the drop jump movement was completed in a non-fatigued state, when landing biomechanics have a tendency to deteriorate from baseline. In addition, this was only a study of the knee joint, and therefore it would be beneficial to investigate changes in the kinematics of the hip and ankle joints as well as for other sports (running, tennis) and movements (cutting, sprinting).

There have also been studies focused more specifically on lower extremity injury incidence in high school runners (Rauh et al., 2006). During the 2006 season, 38.5% of 421 runners sustained at least one injury, which was defined as any reported muscle, joint, or bone problem/injury of the back or lower extremity resulting from running in a practice or meet. Girls sustained a significantly higher overall injury rate (19.6 vs 15 per 1000 exposures for the boys). Predictors of injury for the girls included an injury during the summer before the season and having a quadriceps angle that exceeded 20°. For boys predictors included a history of multiple running injuries and a quadriceps angle greater than 15°. In 2014, Rauh further investigated training-related risk factors for injury and found that runners who did not frequently alternate short and long mileage days, ran for eight weeks or less, and ran a higher percentage of miles on hills or irregular terrain were more likely to be injured during the season (Rauh 2014). Finally, a prospective study of factors leading to stress fractures in 748 competitive runners again found girls at higher risk, with 5.4% of girls and 4.0% of boys affected. The tibia was the most common site in girls, and the metatarsal in boys (Tenforde et al. 2013). Prior fracture was the biggest predictor of future fractures, underlining the need for and the benefits of preventing the initial injury from occurring. Low BMI increased risk for girls, but playing another sport, particularly basketball, seemed protective for the boys. These studies highlight the need for both sex and age-specific studies.

Peak height velocity is not only the period of most rapid bone growth, it is also when bone mineral density is just coming off of its lowest levels (Faulkner et al. 2006) and the cartilage is not yet in its stronger, more mature form. Additionally, the most rapid periods of bone growth tend to precede the lengthening of muscle-tendon complex, which can cause an increase in tensile stress, even at resting positions. Flexibility in boys peaked after PHV, while they saw the greatest gains in measures of strength and explosiveness around the same time as their PHV (Philippaerts et al. 2006). It has also been theorized that the increase in muscle strength is a factor in stimulating bone growth during puberty. For 83 boys and girls between eight and eighteen assessed yearly for six times, peak lean tissue velocity preceded the femur's cross-sectional area velocity and its peak section modulus velocity (Jackowski et al. 2009). The result was the same for both sexes, indicating that the tissue changes are maturity-level and not sex or chronological-age dependent.

During bouts of both high-intensity and intermittent high-intensity exercise, children exhibit less fatigue than adults as defined by force and/or power output (Ratel et al. 2006). Children also showed a smaller decline in step frequency than adults when it came to intermittent running. These results held for both males and females. However, fatigue resistance as measured by an isokinetic dynamometer showed slight differences. While fatigue resistance for the boys gradually declined into adulthood, it plateaued more suddenly around mid-puberty (Dipla et al. 2009). Another characteristic that seems to differ according to sex is shock attenuation. Mercer et al studied eleven boys and seven girls (mean ± SD of ages 10.5 ± 0.9 and 9.9 ± 1.1 years respectively), looking specifically at leg and head peak impact acceleration, as well shock attenuation, the ratio of these two measures (Mercer et al. 2010). The children ran on treadmills at a slow, fast, and preferred speed, as well as once over ground at their preferred speed. While adult shock attenuation ranges from 80-90%, the children exhibited attenuation rates between 66% and 76%. While they had similar shock attenuation, the girls tended to have higher peak leg and head accelerations. It was not clear whether this difference was due to anthropometric characteristics or running technique.

The first study to compare pediatric gait when running overground to on a treadmill found small to no kinematic and EMG differences (Rozumalski et al. 2015). However, the children showed significantly higher hip extension and ankle plantarflexion moments and lower knee extension moments on the treadmill, likely due to a forward movement of the foot center of pressure and higher tendency to forefoot strike as opposed to more rearfoot striking when running overground.

A second study was slightly more targeted, in that its subjects were athletes males age 8-16 on sport-specialized school teams where running and/or sprinting was an important aspect of their sport (Rumpf et al. 2015). Athletes were grouped by their maturational status. Subjects ran on a treadmill, where both vertical and horizontal forces were measured as they performed sprints. The researchers then calculated bilateral limb asymmetry in these measures, as well as in work and power. All groups exhibited asymmetries of between 15% and 20% in horizontal and vertical force, as well as in power. This is in comparison to levels of 2-10% in adults. In addition, pre-pubertal athletes demonstrated significantly higher power asymmetry.

Fourchet et al. had eleven trained male adolescent runners run to exhaustion at a constant speed run and measured contact time and estimated spring mass model characteristics. With fatigue mean foot contact area, contact time, peak vertical ground reaction force, vertical displacement of the center of mass, and leg compression increased significantly. Flight time and leg stiffness decreased, and vertical stiffness, and stride parameters (frequency & length) did not change significantly. Leg compression was calculated by the equation

$$\Delta L = L_0 - \sqrt{[{L_0}^2 - \left(V_{forward} * \frac{T_c}{2}\right)^2] + \Delta z}$$

Where L_0 = initial leg length, T_c = contact time, and Δz = the vertical displacement of the center of mass (Fourchet et al. 2015). Some of the differences between this study and those focused on more anaerobic and intermittent exercise and the reasons for these differences are worth exploring.

The effect of shoe age on running biomechanics was investigated in boys between nine and twelve who participated in any sport at least once a week. After 4 months of use, the boys showed increased loading rate, which is in contrast to adults who showed no change in new versus used shoes. The used shoes also reduced the peak ankle dorsiflexion and increased the ankle plantarflexion at toe-off, which in this case was similar to adult results. These alterations in kinematics came with a significant decrease in the peak ankle. Increased knee power absorption was observed in used shoes (Herbaut et al. 2017). A female shoe study looked at how children in adult shoes performed as opposed to in shoes manufactured specifically for their age group and found that the girls had higher impact forces (2.46 and 2.09 BW) and loading rates (105.85 and 79.78 BW/s) than their adult counterparts. Both metrics were also higher when they were wearing youth sneakers (Forrest et al. 2012). Unfortunately, only kinetics were tested, so there is no way to determine if the changes were solely because of the shoes, or if the runners altered their running kinematics as well, which in turn affected the impact characteristics.

2.2 Inverse Dynamics and Biomechanical Modelling

Musculoskeletal models are a significant tool that allow for the exploration of joint kinematics and kinetics. More importantly, modelling allows for the estimation of muscle and joint contact forces, which can be impractical and/or invasive, particularly when studying youth populations. While EMG can be helpful, what the signal means in terms of the force developed by a muscle, can be affected by numerous factors including muscle length and fatigue, contraction type and velocity, and the contribution of synergistic muscles. As a solution, platforms are incorporating EMG and/or modeling to approximate the roles of individual muscles in movement and force production, as well as how they can coordinate to produce optimal, normal, or disordered movement. OpenSim, an open source software package developed and maintained by Simtk.org, enables users to build, exchange, and analyze such models. It employs sets of differential equations to describe aspects of the musculoskeletal system, such as muscular contraction dynamics. The dynamics of the system can either be found through an optimization problem (for example, to run at a specified speed, or to achieve a certain movement), or it can be set to "track" motion data that has already been captured (Delp et al. 2007).

Existing models can be scaled in accordance with the subject's measurements and/or marker data, by scaling based on the relative distances between the markers. The scaling step adjusts not only bone lengths, but masses, center of masses, muscle lengths, and tendon slack lengths. The next step is an inverse kinematics that uses motion capture data to determine the model's movement and joint angles. The model kinematics are made consistent with measured kinetic data by minimizing the residual in the equation:

$$\vec{F}_{ext} = \sum_{i=1}^{segments} m_i \overrightarrow{a_i} - \vec{F}_{residual}$$

The kinematics from this step are used to find muscle excitations through forward dynamics in computed muscle control (CMC). Static optimization calculates net joint moments into individual muscle forces for each point in time. OpenSim incorporates newly recorded movement data for individualized analysis in the .trc data format, and force plate data in the .sto or .mot format. This results in a simulation of the complete movement including the activations of the involved muscles.

2.2.1 Gait

Several models have been developed with the express purpose of investigating kinematics, kinetics, and muscle activations during gait and running in particular. One such study compared Achilles tendon loading between females running barefoot with different foot strike patterns. Muscle forces for the gastrocnemius and soleus were estimated for 11 rear foot strikers (RFS) and 8 runners non-rear foot strikers. Peak Achilles tendon force occurred earlier in stance phase which contributed to a 15% increase in average Achilles tendon loading rate in the Non

RFS group. This group also experienced 11% greater Achilles tendon impulse with each step (Almonroeder et al. 2013). This results in a significant difference in accumulated stress on the Achilles, and is evidence that forefoot striking may not always be superior. However, these findings could also be used to guide training and conditioning programs to include more Achilles strengthening exercises for non-rearfoot strikers.

Drs. Scott Delp and Tim Dorn have produced a number of models and simulations investigating muscle activations during gait. In 2008, Delp et al investigated contributions to both support and forward progression over a range of walking speeds. The key findings were that the gluteal muscles, vasti, hamstrings, gastrocnemius, and soleus were all primary contributors to support and progression, and that all of their contributions generally increased with walking speed with the exception of the gluteus medius (Liu et al. 2008, p. 2008). Skeletal alignment was also more important to support than muscles at slow walking speeds, whereas at faster speeds, muscular contribution increased, with contralateral soleus muscles providing the propulsion (Liu et al. 2008). A full body model based on a single male subject attempted to include the dynamics of arm motion and found that the arms acted more as a counterbalance to the lower body and did not meaningfully contribute to propulsion or support. The quadriceps were key contributors during breaking and support of the first half of stance, with calf muscles taking over propulsion and support for the second half (Hamner et al. 2010).

Another study examined the changes in forces developed by the leg muscles when running at slow, medium, fast, and sprinting speeds (Dorn et al. 2012). The researchers combined the obtained gait data from nine subjects performing slow running to a full out sprint. They found that the greatest transition in muscle activity occurred at approximately 7 m/s, when running was increasingly powered by upper leg and hip muscles – the iliopsoas, gluteus maximus, and hamstrings – and less by the plantarflexors, soleus, and gastrocnemius that predominate at lower speeds. These results could be implemented in training programs. Broadly, it implies that training of the glutes and hamstrings should take precedence when working with sprinters. On an individual basis, the model could be used to identify relative weakness or imbalances in one of these muscles of importance.

A single-subject study looked at the specific contributions of hamstrings and quadriceps to energy generation and dissipation at the knee joint during the phases of running. A lower-extremity OpenSim model was employed to determine that the quads dissipated energy during flexion and generated energy during extension and the transition from swing to stance phase. The hamstrings dissipated energy during swing phase, and generated energy during stance and the transition from toe-off to swing in flight phase (Yeow 2013). Potential energetic differences in sign or magnitude in adolescent runners would provide clues for training and injury prevention through muscle activation. The Dorn, Schanache, and Pandy group also used OpenSim to isolate the mechanics of the hamstrings during a sprint. They modeled the motion of experienced sprinters to determine the musculotendon strain, velocity, force, power, and work, and how it was divided between the individual hamstring muscles. The setup included surface electrodes for EMG capture. Force generation was generally found to be proportional to the muscle’s cross-sectional area, with the semimembranosus generating the highest force, power, and work. However, the long head of the biceps femoris experienced the highest peak strain and the semitendinosus exhibited the greatest lengthening velocity. From an injury perspective, peak musculotendon force and strains for the semitendinosus, semimembranosus, and the long head of the biceps femoris, were all observed around terminal swing, when most hamstring strains occur (Schache et al. 2012).

A comparison of joint power generation between youth and adult sprinters coming out of the blocks was undertaken by Debaere et al (Debaere et al. 2017). They theorized that differences in joint moments and powers would be the differentiators in increased sprint performance with age, particularly when coming out of the starting blocks. It stands to reason that performance of the task that relies most on the ability of the leg muscles to generate power would be most affected by the changes in pre and post maturational muscle strength, which is about fifteen for boys, but tends to vary more with girls (Abbassi 1998). The study included 14 adult sprinters, and well as 18 sprinters between sixteen and eighteen and 11 sprinters under 16 (average age ~15). In addition to tracking the sprint forces and kinematics, the athletes also performed a countermovement jump as a marker of explosive power. OpenSim was used to calculate joint angles, COM velocity, and lower-body net joint moments and powers. The adult sprinters generated significantly more knee power with higher hip flexion and knee extension during first stance, resulting in longer steps, where in the younger athletes, more power was generated at the hip with shorter steps. The power generation capabilities were also greater in the adult sprinters (Debaere et al. 2017). This study involved both sexes, which may be a confounding factor, as maturation occurs at different ages, and strength differences are much greater after puberty than before. As such, it would be interesting to determine if there is a sex-based difference in percent change in the kinematics, power and/or moments pre and post maturation.

Another study that involved children investigated the contributors to medio-lateral center of mass acceleration during 90° turns and walking (Dixon et al.). OpenSim was implemented to simulate these aspects of gait using experimental motion data. During the turn approach, outside limb soleus and gastrocnemius contribution to lateral COM acceleration was reduced, whereas during the turn itself, inside limb soleus and gastrocnemius contribution increased, and gluteal contribution medially decreased when compared to straight walking, together helping accelerate the COM towards the new walking direction.

2.2.2 Injury Prediction and Prevention

An early study took a lower limb model and employed it to calculate anterior tibial translation (ATT) in both a normal and ACL deficient knee. They then used the model to determine how much quadriceps and hamstring force was necessary to restore ATT to normal, or at the very least an acceptable standard (Shelburne et al. 2005). The force of the leg muscles in the deficient leg was either decreased (quadriceps) or increased (hamstrings). Ultimately, decreasing the quadriceps action was not enough to limit ATT, but increasing the hamstrings action was. It also decreased the knee extensor moment, but not to quite the same degree as the decrease in quadriceps force did. And within the hamstring muscles, the semimembranosus was the most effective at limiting ATT. This suggests that hamstring facilitation, as opposed to quadriceps avoidance is a more effective way to stabilize gait in ACL deficient individuals.

Roldán et al wanted to simulate how the ACL itself behaves under a variety of conditions, including walking, cutting, and jumping (Roldán et al. 2017). They captured 12 participants performing these activities and used the kinematic data in conjunction with a 3 degree of freedom knee model to determine the tensile forces acting on the ACL *in vivo*. The ACL length was calculated by tracking the insertion points from the motion data, and strain was taken from the change from its unloaded length. The greatest elongation and highest tensile forces occurred during a maximal effort two-legged jump. Cutting actually produced lower peak tensile forces than walking, suggesting that ACL injury mechanisms of this type are more likely due to combination loads.

Another common disorder in runners is patellofemoral pain (PFP). However, determining the causality of the muscle forces, pain, and joint stresses has proven difficult. Besier at el (Besier et al. 2009) chose to use an EMG-driven knee model to estimate the muscle forces around the joint in pain-free and patellofemoral pain suffering individuals. The group hypothesized that those with PFP would have decreased action of the vastus medialis compared to the pain free group, and that all subjects would show similar activation patterns whether they were walking or running. In addition to the typical calibration and anatomical models, an EMG-to-activation model and a Hill-type muscle model were used to capture muscle activation and muscle tendon dynamics and forces respectively. Neither hypothesis was found to be true, as the PFP and pain free subjects showed similar quadriceps force distribution, and the distribution of individual muscles changed from walking to running. Interestingly, the females in the study had larger hamstring and gastrocnemius forces in both walking and running, once normalized for height and bodyweight. Since females tend to have higher rates of patellofemoral pain, it may be that this increased muscle activity also changes the joint contact forces, leading to pain.

2.2.3 Physical Therapy and Surgery Outcomes

Another application for forward dynamics modelling is the simulation of the potential outcomes of therapy and surgery, as well as neurological conditions such as cerebral palsy. Fox et al (Fox et al. 2018) chose to simulate the effect of muscle weakness and contracture on the neuromuscular control of normal gait in children. Since both neural and muscular issues affect gait in conditions like spastic cerebral palsy, the group was interested in whether the muscular deficiencies themselves prevented normal gait, or if it was possible to normalize gait via neural control. To this end, walking motion capture and force data for 10 typically developing children were collected, along with medial and lateral gastrocnemius, soleus, and tibialis anterior EMG.

Scaling was used for muscle forces in addition to segment geometry, with the former being scaled to the height squared. They then created multiple musculoskeletal models to simulate varying levels of weakness and contracture by reducing the maximal isometric force of the medial and lateral gastrocnemius, the soleus, and the tibialis anterior by 15 and 30 percent. They reduced the tendon slack lengths by 1.5 and 3 percent. The models that introduced only muscle weakness were still able to achieve normal gait through compensation of other muscles. In the contracture simulations, activity of the gastrocnemius muscles decreased, along with an increase in activity and force production from the tibialis anterior. This was most pronounced during mid stance and swing phase.

An earlier study focused on the how the crouch gait typically experienced by individuals with cerebral palsy affects muscle and joint contact forces (Steele, DeMers, et al. 2012). This is also one of the earlier demonstrations in how modeling can be a useful guide even as models are scaled down and applied to pre-maturational individuals. In this case, the subjects included three healthy children and nine children with cerebral palsy – exhibiting mild (20° – 30°) to severe (> 50°) knee flexion. Motion analysis, EMG data, and modelling found that quadriceps force in severe crouch gait subjects nearly quadruple that found in the mild individuals. This is dangerous as it not only increases the stresses on the tibiofemoral joint, but on the patellofemoral joint and soft tissue like the patellar tendon. Similarly, the peak joint contact force in these individuals was up to six times that of the healthy children, while the subjects with the mild instances of crouch gait exhibited similar levels of tibiofemoral contact forces on the level of 2.5 – 3 times body weight (BW). Results like this are also helpful in determining when surgery may be worth the risks. The children with severe crouch gait are at much higher risk for knee pain and joint degeneration, whereas the individuals with more mild cases would be better served with physical therapy. A similar group combined these two experiments and took both healthy children and children with cerebral palsy. They simulated muscle weakness again by reducing maximal isometric contraction strength until the model produced could no longer reproduce the original subject's gait. Similar to the prior study's findings, quadriceps force increased with crouch gait severity. Both hip abductor and ankle plantarflexor strength decreased linearly with crouch severity (Steele, van der Krogt, et al. 2012). From these results the gluteal muscles and the plantarflexors could be identified as targets for strengthening and physical therapy programs. Van der Krogt later developed a model that incorporated passive muscle properties and motor control aspects by developing a stretch reflex controller to add to a cerebral palsy model (Krogt et al. 2016). One can extrapolate from these applications to how they can be applied in an athletic context, to guide training and injury prevention programs.

As previously mentioned, children can exhibit different and changing neuromuscular and musculoskeletal properties compared to adults, and in order to develop simulations that are accurate and are practically applicable, accounting for at least some of these aspects is necessary. Approaches have included subject-specific MRI information like muscle volume, optimal fiber length, and tendon slack length (Bolsterlee et al. 2015; Fox et al. 2018). Since this is not always possible, others have modified models using body size, height, and mass, or maximum isometric force (Folland et al. 2008; Knarr & Higginson 2015; Knarr et al. 2016; Krogt et al. 2016). Scaling muscle strength to height-squared is a particular example in previous simulation studies involving children.

Leg length discrepancies (LLDs) can be congenital or acquired through injuries or procedures like hip replacements. Scaling one limb on an OpenSim model to generate different discrepancies can provide a guide as to the maximum allowable difference to allow the patient to be able to continue to walk normally, and to minimize future damage and degeneration of the involved and contralateral joints. A study particularly focused on this problem as it relates to a total hip arthroplasty found that the 'safe' LLD was inversely related to the weight of the subject, with the range being 2.1 – 2.6 cm for individuals weighing 50 – 100 kg (Thote et al. 2015).

Computational modelling has also been used to predict the outcomes of rotator cuff repair depending on the supraspinatus reinsertion point. Musculoskeletal models were constructed using a dynamic arm simulator via Matlab and OpenSim, with model parameters like muscle origin and insertion, glenohumeral joint center and center of mass averaged from various prior anatomical studies. Muscle forces and moment arms surrounding the shoulder joint were estimated from insertion 5 – 20 mm in 5 mm increments medially from the original insertion point. As the insertion point moved medially, the supraspinatus moment arm was reduced, particularly in abduction, resulting in a higher necessary force for humeral stabilization, placing increased load on the repaired tendon. Moving the insertion point also decreased the ratio of the compressive to shear force in the glenohumeral joint, lowering the joint's stability (Leschinger et al. 2019). These findings necessitate a cost-benefit analysis of whether these detriments are worth attempting to decrease the tension on the reattached tendon in large rotator cuff tears. Muscle forces estimated from OpenSim can subsequently be used in other types of modeling, including Finite Element Analysis. One example of this looked at how footwear construction influenced the knee biomechanics, where individual bone geometry, motion analysis, OpenSim muscle contributions, plantar pressure, and cadaver data were all used as inputs for a finite element model to determine tissue stresses and strains in the joint (Liu et al. 2016). The process of this dissertation may provide a baseline for the improvement of equipment and footwear designed for particular populations, like female and youth athletes.

Taken all together, there is a clear need for more definitive answers on the potential effects of high-volume distance running in children and young adults. This will provide guidance to parents, coaches, and physicians, and further provide protection for athletes so that they can avoid injury in the short term and extend their potential and capability to participate in an activity well into adulthood. Computational modelling - and OpenSim in particular - allow for the estimation of muscle forces and joint loads so that we can progress towards this end and help develop guidelines, set safe limits on volume, and develop prehab and prevention programs to target weakness and imbalances that may be influenced by age or maturational status.

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CHAPTER 2: THE EFFECTS OF AGE AND FATIGUE ON KINEMATICS AND KINETICS OF FEMALE YOUTH RUNNERS

Abstract

The purpose of this study was to compare the kinematic and kinetic parameters of young female runners before and after a fatiguing run. Motion capture and ground reaction forces (GRF) were recorded before and after a 5-kilometer treadmill run at or close to personal best pace for eleven runners between the ages of 8 and 17. Spatiotemporal parameters, joint angles, GRF, net joint moments, and joint powers were calculated and compared. While it did not reach the level of significance, peak ankle moment and power and hip moment stood out as most affected, all decreasing with fatigue. In terms of age differences, the younger group demonstrated smaller peak knee moment, knee power generation and absorption, but greater maximum external ankle rotation and hip abduction.

Introduction

An increasing number of children and adolescents are training for and participating in long distance running events – in 2013, at least 70,000 children between six and seventeen participated in a half or full marathon (*Running USA's Annual Marathon Report | Running USA*, n.d.). A 2019 survey of state cross country and track and field associations conducted by The National Federation of High School Associations ranks participation in cross country 5th most popular among all possible sports, and 4th among girls, with 488,640 and 219,345 athletes respectively (Howard & Gillis, 2010). There is also anecdotal evidence of middle and high school runners attempting full marathon and even ultra-marathon – any race longer than 26.2 miles – distances. Given that all of these numbers are likely an underestimate, as they only account for official statistics and specific organizations, this represents a significant at-risk population.

Potential injury risk predictors for long distance runners are well studied in the adult population and include leg acceleration knee and leg stiffness, and step length and frequency (Edwards et al., 2009; Heiderscheit et al., 2011; Milner et al., 2007; J. Mizrahi et al., 2000; Joseph Mizrahi et al., 2000; D Y Wen et al., 1997; Dennis Y Wen, 2007). While individuals with a history of tibial stress fractures were shown to have higher values of knee stiffness, lower knee stiffness has been associated with soft tissue injuries. Since long distance running is an activity where both bone and soft tissue injuries are common, the implication of these two findings points to a middle range of optimal leg stiffness. Although adult research is useful in guiding research hypotheses for children and adolescents, results from these studies are often not directly applicable. Reasons for this include special considerations like evolving motor control strategies, imbalances in the maturation rate of bone and soft tissues, and sudden changes in weight and height. In addition, young runners are susceptible to injuries that fully-grown adults are not, including Osgood-Schlatter and Sever’s diseases. While there is evidence that adolescent female runners are more susceptible to tibial stress fractures (Tenforde et al., 2013), there remains a gap in our knowledge about the risk profiles of pre and early adolescents who are running a large number of miles per week.

However, there has been a measure of debate among pediatricians, parents, and sports professionals about safe levels of running volume and frequency with regard to age (Nelson et al., 1990; Rice et al., 2003; Roberts, 2005, 2007). These are issues of significance, as overuse injuries including tibial stress fractures, epiphyseal plate injuries, and patellofemoral syndrome are among the most common musculoskeletal problems in this group. Some of these injuries can lead to long-term disabilities including growth deformities and chronic arthritis; therefore, identifying the individuals at high risk for these outcomes and the opportunity to prevent them is worthwhile.

The majority of investigations into youth running gait are focused on short, maximal efforts like sprinting (Yanagiya et al., 2003)(Rumpf et al., 2015), including adult/youth comparisons (Aeles et al., 2018). Some have utilized EMG data, looking for differences between treadmill and overground running (Rozumalski et al., 2015), or differences in levels of co-contraction in different age groups (Frost et al., 1997). In one more directly distance-based comparison, Liley et al found that older female runners exhibited higher rearfoot eversion, knee internal rotation, and knee adductor moments than their younger counterparts (Lilley et al., 2011). However, as the younger group included subjects between the ages of 18 and 24, it likely did not capture any individuals that were not already at a full maturational stage.

The effects of fatigue on running mechanics have also been studied in adult runners, with a variety of outcomes depending on the population and the experimental setup. Some of the reasons for sometimes conflicting results are because there can be significant individual variation in biomechanics to begin with. For example, there have generally been smaller effects on ground reaction forces (Dierks et al., 2010; Luo et al., 2019), or in some cases even decreases (Gerlach et al., 2005). Step and stride length do tend to decrease with fatigue (Joseph Mizrahi et al., 2000; Williams et al., 1991). In addition, more experienced and faster runners tend to exhibit fewer and smaller kinematic changes with fatigue, with one of the bigger differences being greater hip abduction in novices (Luo et al., 2019, p.; Maas, Bie, et al., 2018). In a fatigued state, female runners have also been shown decreased dorsiflexion and increased knee flexion (Kellis & Liassou, 2009; Miller et al., 2007a).

The purpose of this study was to compare the kinematic (joint angles) and kinetic (ground reaction forces, and joint moments, and powers) parameters of young female runners of different age groups before and after a fatiguing run. Our hypothesis was that stride length would decrease and ground reaction forces would remain relatively similar across groups and time. Furthermore, we expected there would be an increase in knee flexion and decrease in dorsiflexion with fatigue, and that the younger runners would exhibit greater changes at the hip and knee joints than the older runners.

Methodology

Participants

Eleven female children and young adults between the ages of eight and seventeen were recruited for this study. Participants were from Atlanta area middle and high school cross country teams and running clubs and recruited through flyers and word of mouth. All had been running one a week or more for at least a year and had experience running a timed distance of at least three kilometers. Of those who qualified via the inclusion criteria, those who had experienced a lower-extremity injury in the 6 months prior to data collection that kept them from competing or training for more than one week were excluded from the study. In order to participate, subjects had to have run a timed 5-kilometer distance within the past year, to ensure they were able to run the required distance, as well as to give a guide time for the treadmill run. Permission for recruitment and the study was obtained from the Georgia State University Institutional Review Board. A parental permission form for each subject was signed by the parent, with written assent obtained from the participants aged 11-17 years, and verbal assent obtained from the participants 10 or younger.

Instrumentation

Participants ran over two AMTI force plates (Advanced Mechanical Technology Inc., Watertown, MA) embedded in the middle of a 10 m walkway, plus additional runway in order to properly accelerate. An eight-camera Vicon motion capture system (Vicon, Centennial, CO) captured kinematic data at a frequency of 100 Hz, accompanied by the VICON lower-body plug-in-gait (PIG) marker placement on the subjects. PIG employs 16 reflective markers bilaterally at the anterior superior iliac spine, posterior superior iliac spine, thigh, knee, shank, ankle, heel, and toe (Figure 2). Ground Reaction Force (GRF) data were synchronically collected at a frequency of 1000 Hz.

Experimental Design

After arriving at the lab, the parent or guardian signed a parental permission form and the subjects 11 years or older signed a written assent form, with those under 11 giving informed verbal assent. Then the subject, with assistance from the guardian if needed, answered questions about their training, including the following:

- How many days per week they run
- How many miles per week they run
- At what age they began participation in distance running
- Other sports they participate in
- Any prior injuries they have had that kept them from participating in physical activity.

Participants' height (m) and body mass (kg) were measured using a standard scale with a height rod. Anthropometry parameters such as leg length, knee width, and ankle width were measured on both sides of the body using a caliper and a tape measure. Based on average developmental ages, subjects were separated into 2 age groups to determine if there was a difference in how fatigue affected younger, potentially pre or mid-pubertal runners (14 and under) compared with those aged 15-17 (Herman-Giddens 1997, Brix 2019).

Table 1. Mean (SD) of subject characteristics

	N	**Age**	**Height (m)**	**Weight (kg)**
8-14	5	11.8 (2.5)	1.43 (0.13)	31.8 (8.2)
15-17	6	16 (0.9)	1.63 (0.07)	53.4 (3.8)
Total	11	14.1	1.54 (0.14)	43.6 (12.7)

Subjects were asked not to run in the 24 hours before data collection, so as to limit baseline fatigue without unnecessarily impacting any training the subjects may need to complete. Subjects were instructed to wear their typical running attire, with either fitted tights or shorts that ended at least 2-3 inches above the knee in order to aid in marker placement and reduce marker obstruction. After the aforementioned data was collected, the runners were provided an opportunity for a self-directed stretch and warm up on the treadmill for familiarization. After warmup, subjects were marked and a total of 16 retroreflective markers were placed in accordance with the VICON lower body plug-in-gait model (**Figure 1**).

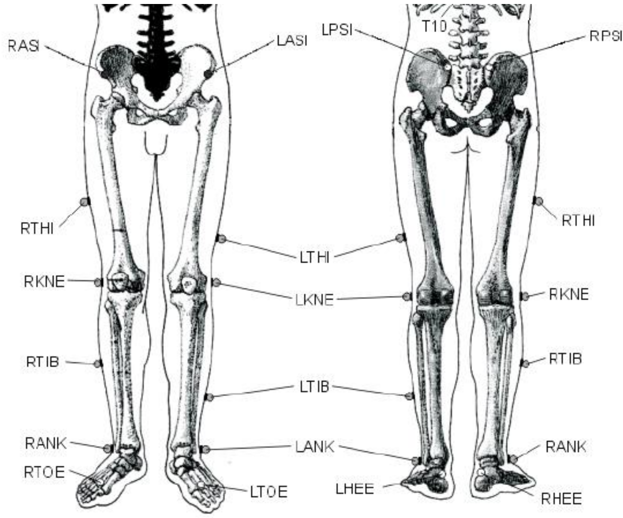


Figure 1 Vicon Plug-in Gait Marker Placement

After warm up and marker placement, subjects ran down the gait lab walkway in order to obtain at least 3 acceptable foot contacts from each limb with the force plate. Each trial used for analysis was checked to ensure that the subject was within 0.5 m/s of their average speed (Table 2). After collection, subjects performed a 5K on a treadmill in or next to the biomechanics lab. The run was completed at a pace at or near their personal best given on the intake questionnaire. Upon completion of the treadmill run, subjects were inspected for loose and/or missing markers. Loose markers were secured, and missing markers were replaced on the areas pre-marked with ink on the skin or tape on clothing. With as little time passing as possible, post-run data was then collected in the same manner as the pre-run data.

Data Analysis

Measured parameters

Vicon Nexus (Vicon, Centennial, CO) was used for processing the raw data of the running trials and calculating the spatiotemporal parameters. VICON Polygon (Vicon, Centennial, CO) generated the pertinent gait parameters, and compared to those produced by OpenSim (NCSRR, Palo Alto, CA). Relevant gait spatiotemporal parameters compared include stride length and cadence. Stride length was measured in meters as the anterior-posterior distance between successive foot strikes of the right or left foot as determined by the heel marker. Foot strike was defined as the beginning of a gait cycle and identified using either the heel or toe depending on the participant's foot strike pattern. Also included were peak hip and knee flexion and extension, peak ankle dorsiflexion and plantarflexion, peak hip abduction and adduction, and peak ankle internal and external rotation. Ground reaction forces (GRF) were normalized by body weight. Peak joint powers and moments for the hip, knee, and ankle were normalized by body weight and leg length. VICON Plug-in-gait was used to calculate time-distance parameters and lower-limb kinematics, and kinetics.

Statistical analysis

The aspects examined were spatiotemporal variables, including stride length and cadence, as well as peak kinematic variables, ground reaction forces, net moments, and powers. For each subject, the three best trials for each condition were averaged. Differences were tested using a two-way mixed analysis of variance with one dependent factor (time: pre vs post run) and one independent between subjects factor (age: young vs old children). The significance level was set at $\alpha = 0.05$. SPSS 22 (IBM Corp., Armonk, NY) was used to conduct statistical analysis.

Results

The overall analysis revealed a significant interaction between age and time ($F(1,9) = 357.60$, $p = 0.041$); also, there was a trend for significance pre and post-run ($F(1,9) = 196.88$, $p = 0.055$).

Spatiotemporal parameters

While cadence did decrease to some degree post-run, stride length remained almost exactly the same. There was similarly no significant effect of age on these spatiotemporal parameters (Table 3). The younger group did appear to have a slightly shorter stance viewed as a percent of the gait cycle.

Table 2. Mean ± standard deviation of pre and post-run cadence, stride length, ground reaction forces, and trial speed.

	Pre	Post	*p*
Cadence (steps/min)	177.82 ± 9.99	171.51 ± 14.40	0.336
Stride Length (m)	2.21 ± .27	2.21 ± .33	0.946
Peak GRF (xBW)	2.45 ± .15	2.40 ± .08	0.302
Speed (m/s)	3.42 ± .36	3.51 ± .47	0.124

Table 3. Mean ± standard deviation of cadence, stride length, ground reaction forces, and trial speed by age group

	Younger	Older	*p*
Cadence (steps/min)	184 ± 11.27	172.55 ± 4.98	0.187
Stride Length (m)	2.01 ± .26	2.31 ± .27	0.316
Peak GRF (xBW)	2.47 ± .11	2.43 ± .19	0.411
Speed (m/s)	3.48 ± .41	3.46 ± .34	0.122

Kinematic variables

Contrary to our hypothesis, there was no significant difference in knee kinematics with pre and post, nor were there differences between the age groups, only a small non-significant decrease in swing phase knee flexion. There were also small changes in peak plantarflexion (+24.4°) and dorsiflexion (-5.5°) (Figure 2). The younger group also showed nearly significant amounts more hip abduction and external ankle rotation (**Error! Reference source not found.**).

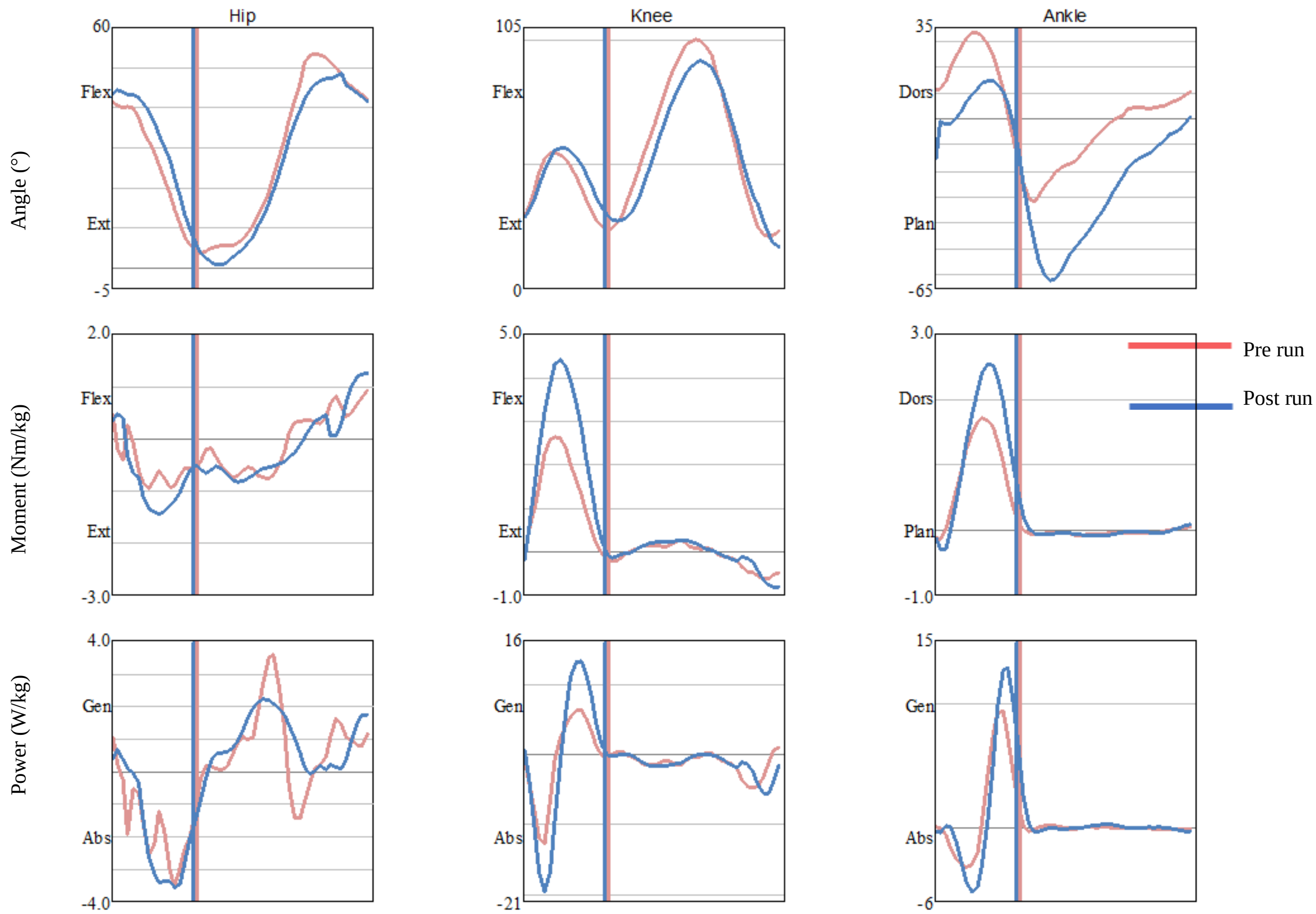


Figure 2. All-subject averages as a percentage of gait for pre-run (red) and post-run (blue) joint angles, moments, and powers in the sagittal plane of the hip, knee and ankle.

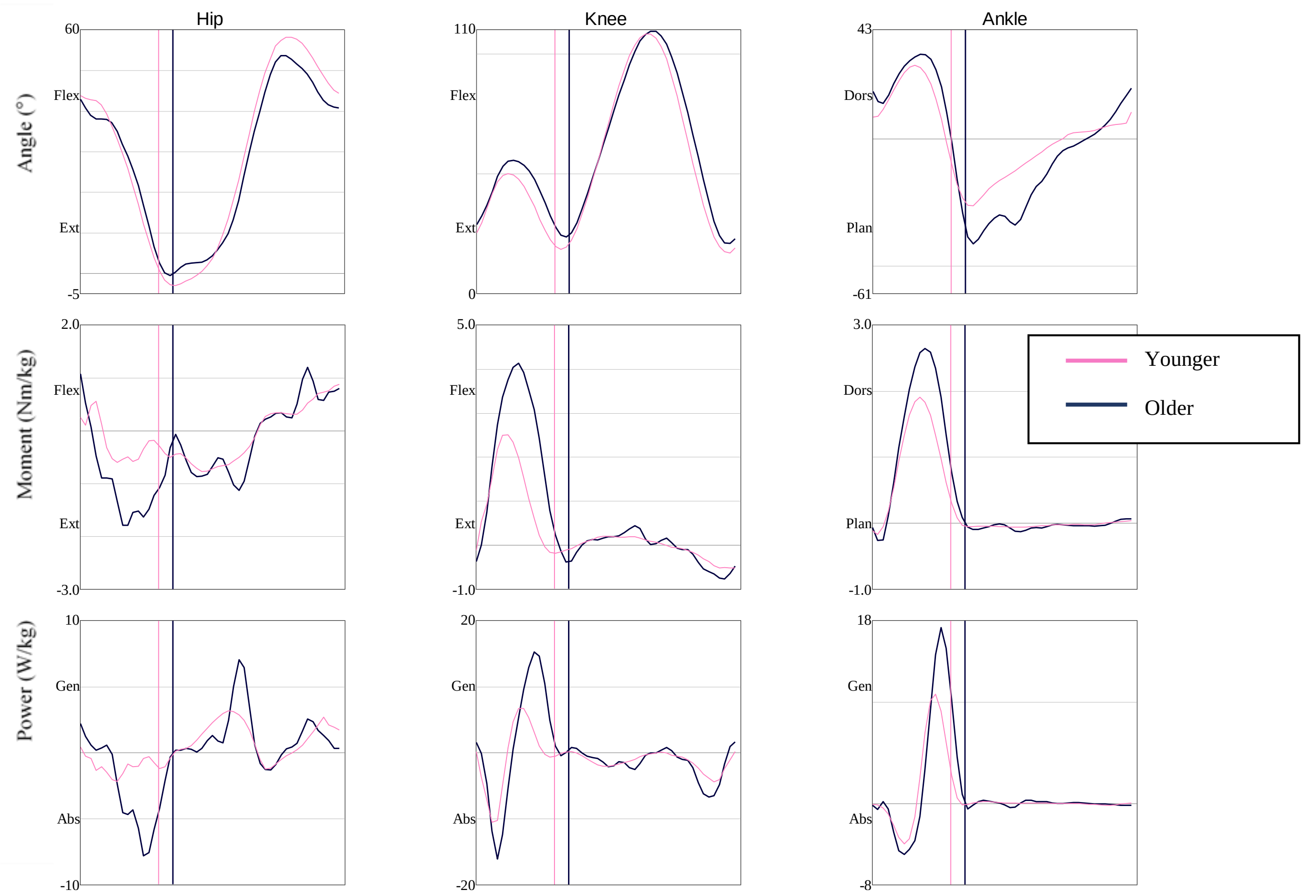


Figure 3. Joint angles, moments, and powers in the sagittal plane for the younger group (pink) and older group (navy).

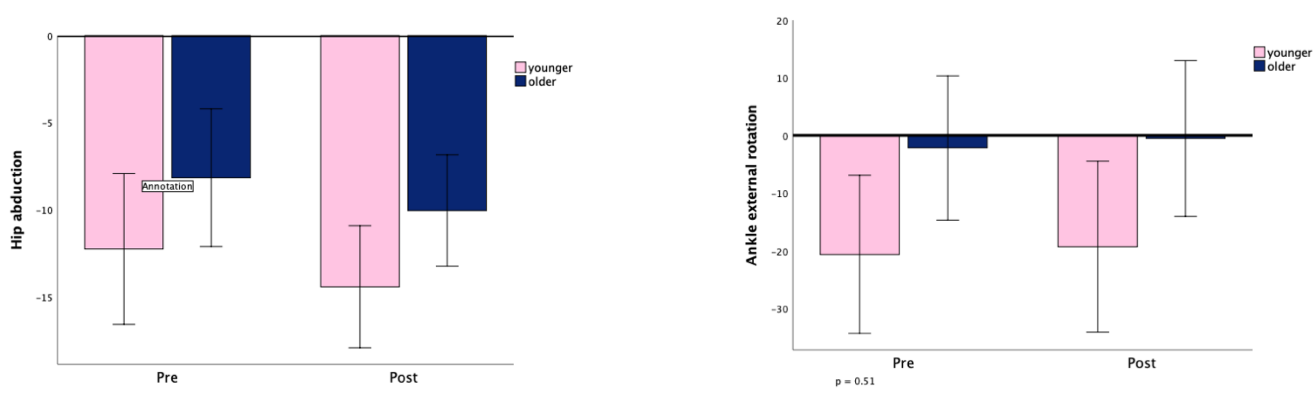
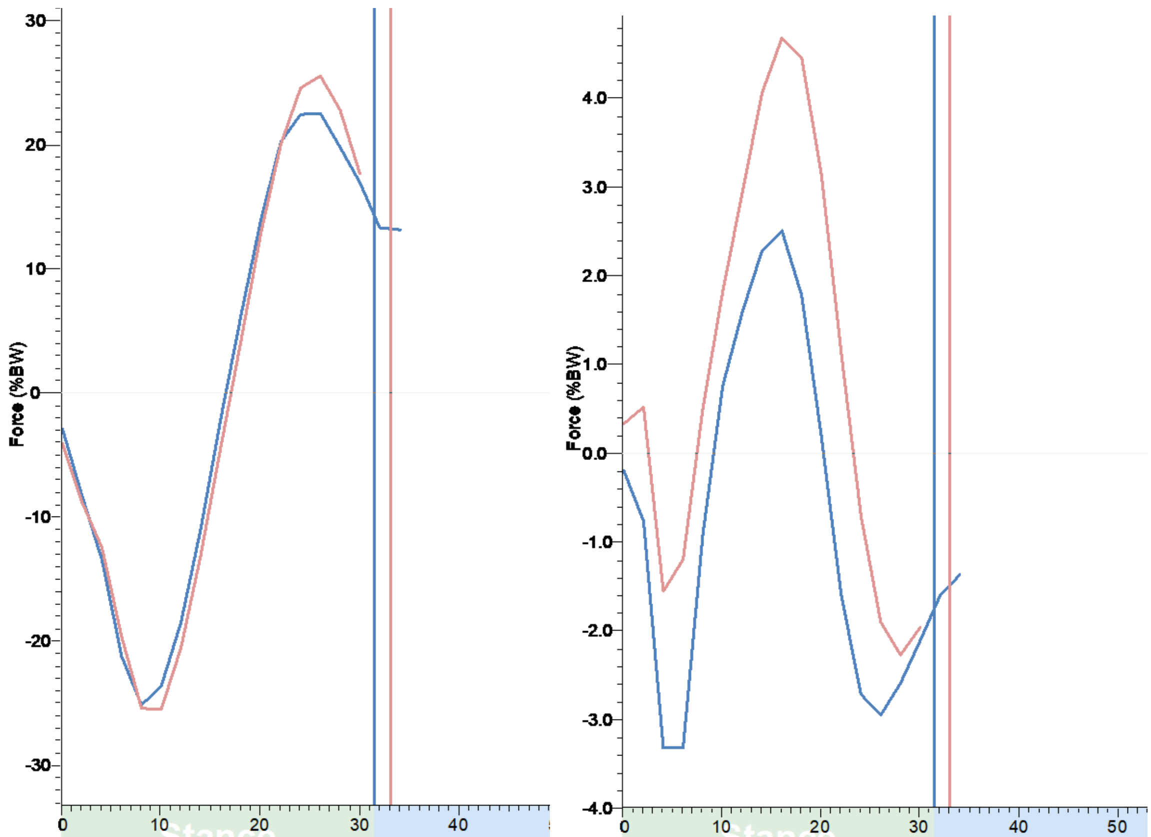


Figure 4. Pre and post run age differences in hip abduction and external ankle rotation in degrees.

Kinetic Variables

Peak ground reaction forces decreased only slightly after the run (Figure 5). The difference between the age groups was also minimal. At the joints, the ankle was most affected by fatigue, with both ankle moment and ankle power increasing noticeably but not quite reaching the set significance level (Table 4). Meanwhile, hip adduction moment decreased, and aside from a slight increase in knee power and moment, there were no notable differences in any other of the kinematic variables measured based solely on fatigue.



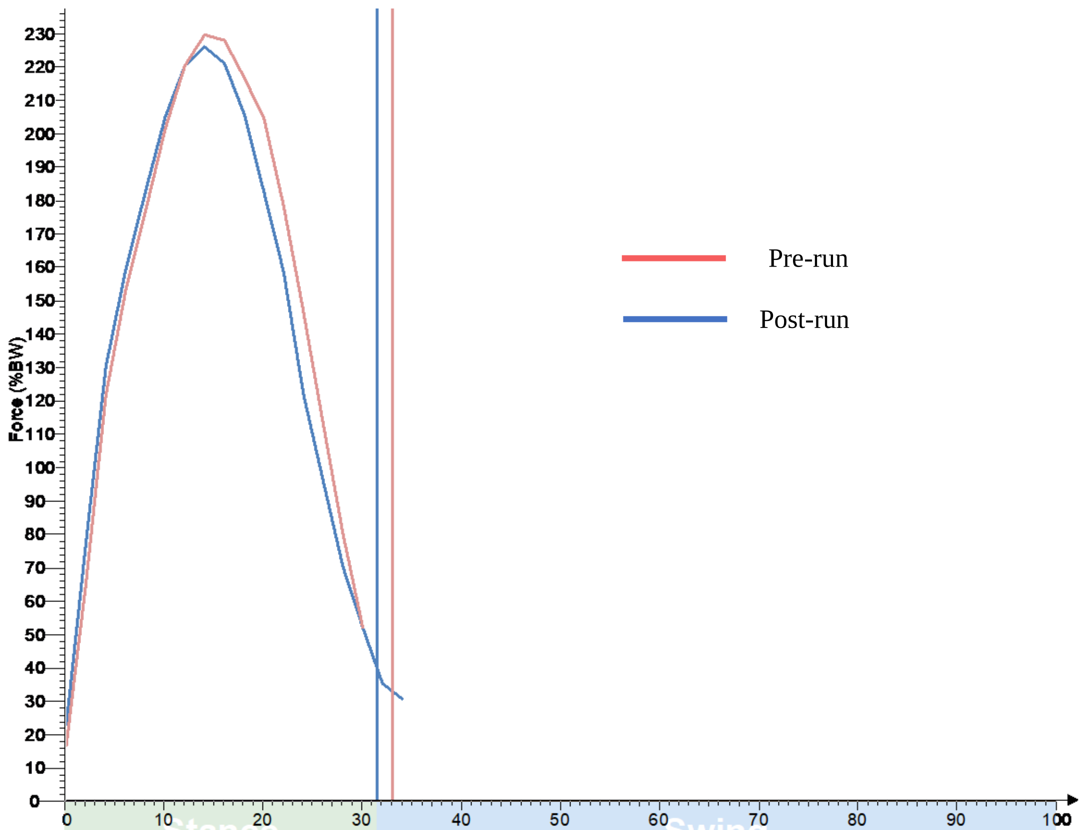


Figure 5. Ground reaction forces in the anteroposterior (AP), mediolateral (ML), and vertical directions as a percentage of the gait cycle .

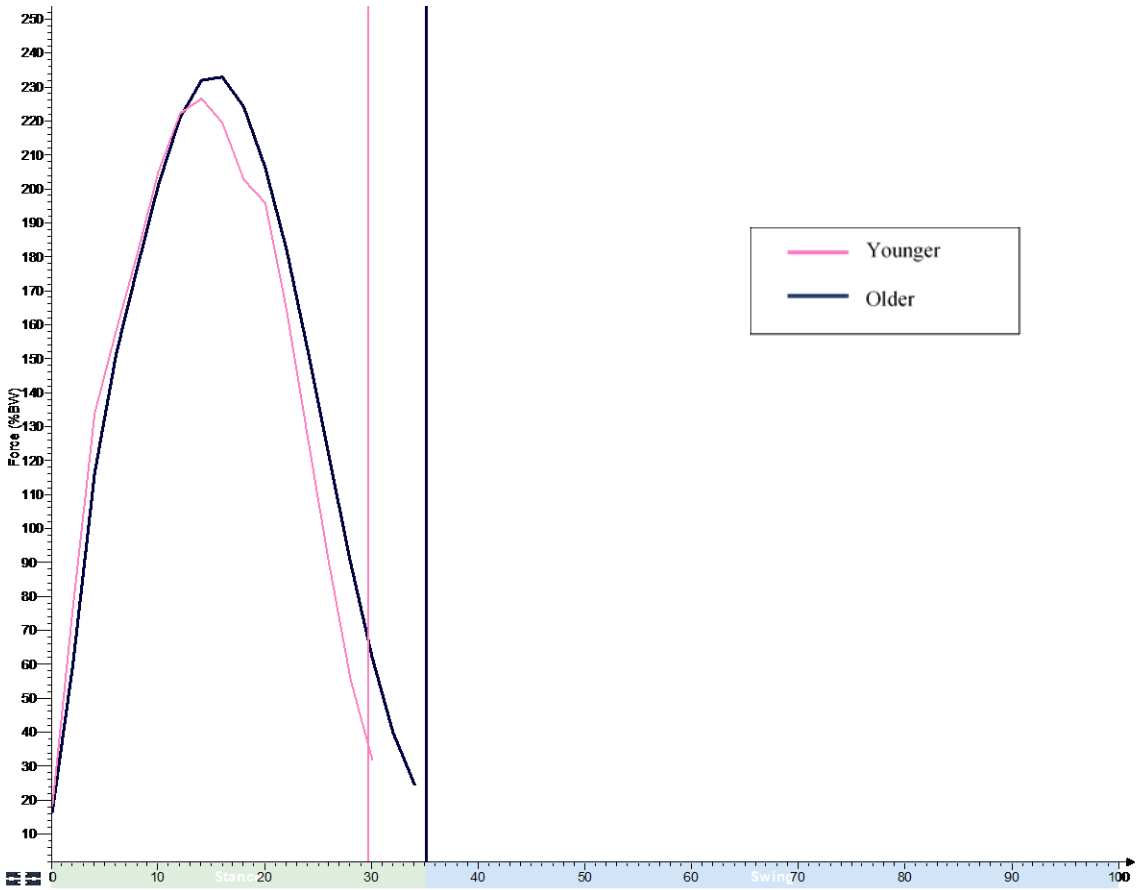


Figure 6. Averaged normalized ground reaction forces in the vertical direction for the younger (pink) and older (navy) groups.

Table 4. Pre and post peaks for the kinetic variables most affected by fatigue.

	Pre	Post	F	*p*
Ankle power	12.51 ± 3.41	13.68 ± 2.17	4.71	0.058
Ankle moment	2.06 ± .45	2.24 ± .34	4.16	0.072
Hip add moment	11.32 ± 4.09	10.5 ± 3.23	4.26	0.069

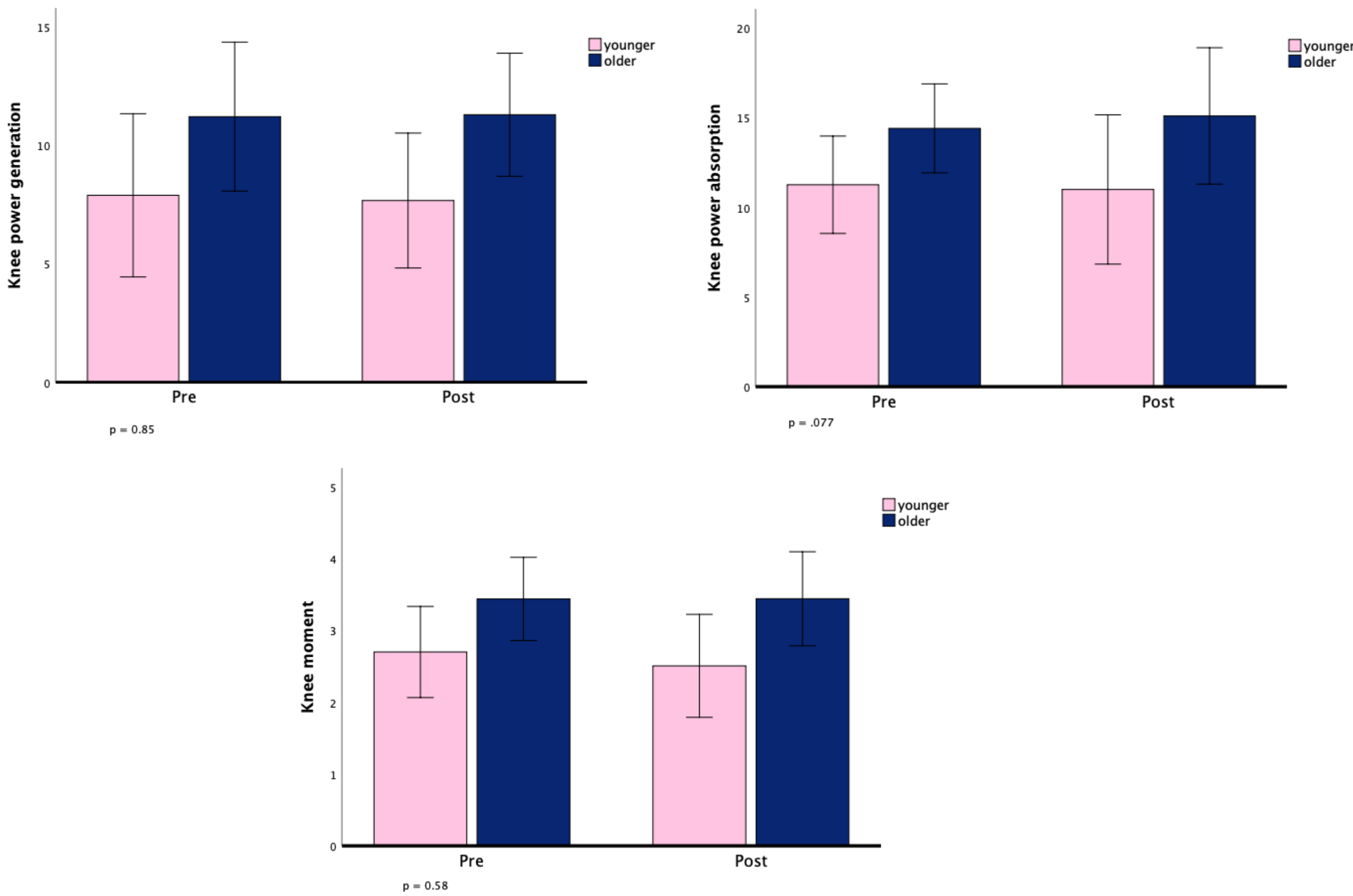


Figure 7. Differences between ages pre and post run for hip abduction and external ankle rotation (degrees) and knee power generation and absorption (W/kg).

Regression Analysis

A simple regression was performed to determine the relationships between age and cadence, ankle rotation, and knee moment. There was a significant relationship for cadence (F(1,9) = 7.61, $p = 0.22$) with an R^2 of 0.458, and knee moment (F(1,9) = 9.39, $p = 0.13$), with an R^2 of 0.511. Cadence decreased 2.5 steps/min for every year, and knee moment increased 0.19

Nm/kg with every year. There was not a significant relationship between age and ankle rotation ($F(1,9) = 4.93$, $p = 0.53$), $R^2 = 0.282$.

Discussion

The results of the study characterize the differences in lower limb kinematics and kinetics before and after an all-out distance run in girls at different age levels. Looking only at fatigue effects, there were small but not significant changes before and after the run. While this confirms our hypothesis with regards to ground reaction forces, it runs counter to our other hypotheses. For example, stride length remained essentially unchanged. There was also very little change in knee kinematics, both by age and by fatigue. This is surprising given this seems to be one of the changes that are generally consistent across adult studies. One result that did produce similar trends to adult studies, although not to a significant degree, was the increase in plantarflexion during swing phase (Maas, De Bie, et al., 2018) and decrease in dorsiflexion (Kellis & Liassou, 2009), which were more statistically significant in adult female runners.

One potential explanation for the small changes before and after the run is that the protocol did not sufficiently produce fatigue in the subjects, or at least not universally across all of them. This may also explain the small degree of changes in spatiotemporal parameters, since most adult-based studies typically find some significant difference in this area. Similar studies have allowed for self-selected speeds (Brown et al., 2014; Miller et al., 2007b; Williams et al., 1991), or a universal speed performed until fatigue (Luo et al., 2019). Others pre-fatigued selected muscles (Christina et al., 2001; Kellis & Liassou, 2009), employed the Borg scale (Koblbauer et al., 2014; Maas, Bie, et al., 2018), or VO_{2max} (Gerlach et al., 2005) as a measure of fatigue. Protocols involving heart rate monitors are another potential solution to gauging fatigue levels.

When separating groups by age, the dependence of changes with fatigue produced unexpected results with kinematics in hip abduction and external ankle rotation. The increase in hip abduction with the younger runners mirrored the differences found between novice and competitive runners (Maas, Bie, et al., 2018). This may point to the fact that some of the differences between younger and older runners may be influenced by the amount of time they have been engaged in running, rather than by maturational differences. Increases in eversion have been found in adults (Dierks et al., 2010), so it's not immediately clear why there is such a difference between the older and younger runners. Results did confirm our hypothesis at the knee joint. These results coincide with findings of studies examining the mechanics of young sprinters (Debaere et al., 2017). Compared to their older counterparts, younger sprinters tend to demonstrate smaller knee extension moment at sprint starts. In addition, a smaller percentage of their total lower-body power is derived from their knees compared to their hips and ankles. Other studies looking at sprinting as a whole also found that sprinting performance was much more dependent on ankle power generation during stance for younger sprinters, whereas knee power was a bigger contributor to performance in adults (Aeles et al., 2015, 2018). From our results, it appears that this applies for power absorption during running as well. Girls don't typically reach full ability to generate power until about the age of 12 (Malina et al., 2004). This is derived from not-yet fully developed ability to generate power, particularly in the knee extensors (Gissis et al., 2006). This shifts the power generation during stance phase to the ankle, which could become more pronounced with fatigue, since the knee is acting from a position of relative weakness to begin with.

One of the limitations in this study is the number of subjects. A number of the age-related differences were close to reaching the significance level, with effect sizes ranging from 0.29 for knee power generation to 0.36 for ankle rotation. As mentioned there can be wide variability in runner's kinematics, therefore studies with larger groups are necessary in order to generate robust group trends and meanwhile examine the potential influence of individual variations. Another limitation was that subjects were grouped by age with the assumption that the average girl finishes puberty around the age of 14 years. To this end, the employment of MRI, maturational status questionnaires, or onset of menarche can better divide runners into appropriate maturational groups, as age is not a perfect proxy for this measure. An instrumented treadmill in conjunction with a motion capture system would also allow for better control over the subjects' speed when measurements are taken, provide more foot falls to choose from, and would allow for easier data collection at multiple points along the run. Multi-year prospective studies performed with groups of runners that takes regular kinematic and kinetic measurements and tracks injuries can provide still more detail as far as potential injury markers.

Further investigations could help determine whether variances in gait are the result of inherent differences in muscular capabilities from the start, or in the neuromuscular responses to fatigue. And within that fatigue, are the alterations due to central nervous system and pathway factors, peripheral to the neuromuscular junction and occurring within the muscle itself, or some combination thereof. General consensus for repeated maximal voluntary contractions is that fatigue progresses along with age through adulthood. However, it is not clear that we can assume the same for long-term, non-maximal activity that depends more on slow-twitch fibers. A study of maximal voluntary isometric contraction concluded that while children and adolescents experience more central fatigue than adults, adolescents experience more peripheral fatigue given equal amounts of central fatigue (Piponnier et al., 2019). When incorporating gender differences, fatigue rates for females during intermittent high-intensity exercise appear to reach adult levels more abruptly, somewhere during mid adolescence (Dipla et al., 2009). Such results underscore the importance of dividing children into pre-pubertal, adolescent, and young adult categories, particularly when discussing athletic performance and training.

Conclusions

This study showed that as younger runners progress during a run, the most significant changes in both kinematics and kinetics occur at the ankle joint, particularly as it pertains to plantarflexion and dorsiflexion. More power was being generated by the ankle as opposed to the knee in the younger group, and it appears that this trend increases along the run. Coaches and parents of younger runners should be cognizant of such differences, and perhaps consider adding knee extensor strengthening exercises to both protect the ankle and optimize running performance.

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CHAPTER 3. THE EFFECTS OF AGE AND FATIGUE ON MUSCLE FORCES IN FEMALE YOUTH RUNNERS

Abstract

There is disagreement between stakeholders in the well-being and performance of young athletes how much running volume is appropriate and at what age, and whether too much too soon can produce negative long-term outcomes. To investigate the effects of fatigue on young female distance runners, the motion and ground reaction forces of 10 girls between the ages of 8 and 17 were recorded before and after an all-out 5-kilometer run. The inverse kinematics and static optimization tools in the OpenSim modeling software were used to estimate the muscle forces, and how they changed with fatigue. Muscle forces were significantly different before and after the run, particularly at the knee. Fatigue affected the age groups differently at the hip abductors and the ankle joint, with the younger runners typically exhibiting higher muscle forces as a percentage of their body weight, with steeper decreases post-run. These results have implications and suggest that age-based volume limits may be beneficial for young runners.

Introduction

Running is one of the earliest and most instinctual types of exercise we learn to engage in. It is a popular sport and an accessible leisure activity that is low in cost, and has numerous physiological benefits, including cardiovascular fitness, bone strengthening, and prevention of diseases like diabetes (Jenny & Armstrong, 2013). Cross country and track and field are one of the biggest areas of high school sports participation, especially among girls (Post et al., 2017). While shorter, more intense bouts of running have always been common and part of games children play, in the past few years, young athletes are running more often, for longer distances, and more competitively. Significant numbers are even starting to run ultramarathons, with distances that exceed even the 26.2 miles traversed in a marathon (Scheer et al., 2020). Despite this, there is no current set of guidelines as to what volume of running is safe at what ages of development, similar to a sport like baseball with its recommended pitch counts and rest days.

One way to inform potential participation recommendations is investigating how biomechanics change with fatigue in younger populations. Motion analysis has provided some information as to what characteristics change with fatigue in adult runners, including increased hip and knee range of motion (Luo et al., 2019), and decreased stride frequency (Joseph Mizrahi et al., 2000). There have also been comparisons between different levels of experience and training that show novice runners exhibit greater changes in biomechanics with fatigue than their competitive counterparts (Maas et al., 2018), and that faster marathoners maintain peak knee flexion magnitudes during stance phase better than slower runners (Chan-Roper et al., 2012). One study that looked directly at muscle activations at various speeds and across various age ranges in children, found that the younger the age group, the more likely they were to demonstrate high levels of co-contraction at both the thigh and the shank, and therefore a higher metabolic cost of locomotion (Frost et al., 1997).

Studies of running using OpenSim have looked at which muscles contribute to propulsion and support, finding for example that the quadriceps were most responsible for breaking, whereas the soleus and gastrocnemius were most involved in propulsion and support (Hamner et al., 2010). Others have found that for most of the muscles they looked at, force generated per unit of activation was significantly related to running speed (Arnold et al., 2013). Dorn et al validated the accuracy of OpenSim force estimations matching EMG data to muscle forces at various running speeds. At a running speed of about 3.5 m/s, for example, peak force developed by the muscles ranged from .17 times bodyweight for the tibialis anterior to 6.7 times bodyweight for the soleus. A child-specific application, individual maximal isometric forces were applied to a model investigating the estimated muscle forces during gait for individuals with cerebral palsy, where maximum muscle forces ranged between approximately 0.1 (dorsiflexor) and 1.8 (hip extensor) times subject bodyweight during walking (Kainz et al., 2018).

There are studies investigating differences in running biomechanics between children and adults, but a number of them focus on either sprinting or its role of running in the context of another sport. Fewer still have investigated changes related to fatigue. No studies exist investigating the potential long-term outcomes of pre-maturational long-distance running. The use of modeling that allows for estimation of joint loads and muscle contributions has potential to become a tool in talent identification, performance enhancement, and injury-risk assessment. As an initial step to this end, the purpose of this study was to use a musculoskeletal model of the lower extremity to estimate muscle forces during running in young female runners, as well as how they may change with fatigue. The hypothesis of this study was that: 1) muscle forces at the knee will decrease for both younger and older female school-age runners, 2) decreases in knee muscle forces will be greater for the younger group of runners and 3) younger runners will see changes with fatigue at the ankle joints, particularly those involved in dorsiflexion.

Methodology

Participants

Eleven female children and young adults between the ages of eight and seventeen were recruited for this study. One subject was excluded from the study as the error result of the inverse kinematic tool could not be reduced to an acceptable level. Participants were from Atlanta area middle and high school cross country teams and running clubs and recruited through flyers and word of mouth of coaches and teammates. All had been running for at least a year and had experience running a distance of at least five kilometers. Those who had experienced a lower-extremity injury in the 6 months prior to data collection that kept them from competing or training for more than one week, or those who had not had a training week of at least 10 miles were excluded from the study. The study protocol was approved by the Georgia State University Institutional Review Board. A parental permission form for each subject was signed by the parent, with written assent obtained from the participants aged 11-17 years, with verbal assent obtained from subjects under 10 years.

Table 5. Mean (SD) of subject characteristics.

	N	**Age**	**Height (m)**	**Weight (kg)**
8-14	4	12 (0.1)	1.46 (0.14)	32.8 (9.2)
15-17	6	16 (0.9)	1.63 (0.07)	53.4 (3.8)
Total	10	14.4	1.56 (0.13)	45.1 (12.2)

Instrumentation

Participants ran over two AMTI force plates (Advanced Mechanical Technology Inc., Watertown, MA) embedded in the middle of a 10 m walkway. As studies have shown no significant difference in kinematics due to fatigue by limb, left or right strikes were noted but analyzed as the same. An eight-camera VICON motion capture system (Vicon, Centennial, CO) captured kinematic data at a frequency of 100 Hz, accompanied by the VICON lower-body plug-in-gait (PIG) marker placement on the subjects. PIG employs 16 reflective markers bilaterally at the anterior superior iliac spine, posterior superior iliac spine, thigh, knee, shank, ankle, heel, and toe. Ground Reaction Force (GRF) data were collected simultaneously at a frequency of 1000 Hz.

Vicon Nexus (Vicon, Centennial, CO) was used for processing the raw data of the running trials and calculating the spatiotemporal parameters. VICON Polygon (Vicon, Centennial, CO) generated the pertinent gait parameters, and compared to those produced by OpenSim (NCSRR, Palo Alto, CA). OpenSim was also used to generate contact and muscle force predictions from marker data. Custom and open source Matlab (The Mathworks, Inc., Natrick, MA) programs and toolboxes were used to convert kinematic and kinetic data for use in OpenSim.

Experimental Design

Participants' height (m) and body mass (kg) were measured using a standard scale with a height rod. Anthropometry parameters such as leg length, knee width, and ankle width were measured on both sides of the body using a caliper and a tape measure. Based on average developmental ages, subjects were separated into 2 age groups to determine if there was a difference in how fatigue affected younger, potentially pre or mid-pubertal runners (14 and under) compared with those aged 15-17. The subjects also answered questions about their training, including the following:

- How many days per week they run
- How many miles per week they run
- At what age they began participation in distance running
- Other sports they participate in
- Any prior injuries they have had that kept them from participating in physical activity.

Subjects were asked not to run in the 24 hours before data collection, so as to limit baseline fatigue without unnecessarily impacting any training the subjects may need to complete. Subjects were instructed to wear their typical running attire, with either fitted tights or shorts that ended at least 2-3 inches above the knee in order to aid in marker placement and reduce marker obstruction. After the aforementioned data was collected, the runners were provided an opportunity for a self-directed stretch and warm up on the treadmill for familiarization. After warmup, subjects were marked and a total of 16 retroreflective markers were placed in accordance with the VICON lower body plug-in-gait model.

After warm up and marker placement, subjects ran down the gait lab walkway in order to obtain at least 3 acceptable foot contacts with the force plate. After collection, subjects performed a 5K within 30 seconds of their personal best pace on a treadmill in or next to the biomechanics lab. Upon completion of the treadmill run, subjects were inspected for loose and/or missing markers. Loose markers were secured, and missing markers were replaced on the designated marked areas on skin or clothing. With as little time passing as possible, post-run data was then collected in the same manner as the pre-run data, with all subjects running within 0.5 meters per second of their pre-run collection speed.

Modelling

The marker trajectories and force data collected were employed to estimate joint reaction and muscle forces, and muscle forces in the OpenSim software (Opensim 4.1, Oracle Corporation). The model adapted for this study was the Gait2392 generic plug-in-gait (PiG) model developed by Arnold, Rajagopal, Dunne, and Carty. This is a lower extremity model that takes the original Gait2392 Opensim model and incorporates the VICON plug-in-gait marker set. The default model has a mass of 40.928 kg, which was scaled to the individually collected subject weight (**Error! Reference source not found.**). The inertial properties of body segments, joint articulations, muscle moment arms, muscle attachments, and muscle length properties were scaled as a function of both length and body mass.

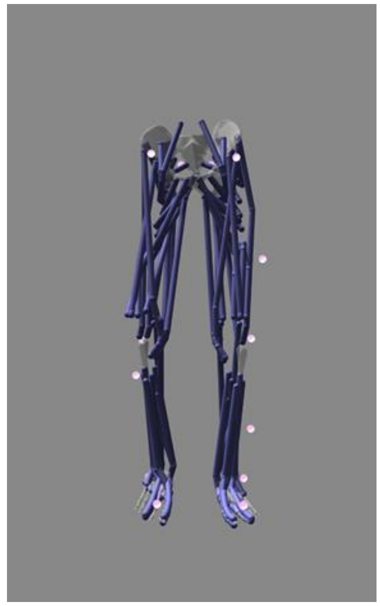


Figure 8. Scaled opensim model (Subject 8)

Marker positions (.trc) and motion (.mot) files for each trial were obtained through the export pipelines provided within the VICON Nexus Software. The marker positions were used as inputs in the inverse kinematics tool which goes frame by frame through the trial markers to best reproduce the motion captured in the lab environment in the model with minimal marker and coordinate errors. The c3d2OS script in the MOtoNMS (Mantoan et al., 2015) Matlab toolbox transformed the Nexus produced .csv file containing forces, moments, and center of pressure into a format (.mot) suitable for input into OpenSim for static optimization.

In order to obtain muscle force estimates, static optimization was performed on the scaled models. The static optimization tool uses the known motion of the model to solve the equations of motion for the unknown generalized forces

$$\sum_{m=1}^{n}(a_m F_m^0)R_{m,j} \quad = \tau_j$$

while minimizing the following for each joint:

$$\sum_{m=1}^{n}(a_m)^p$$

where n is the number of muscles in the model, a_m is the activation level of muscle m at a discrete time step, F_m^0 is the mucle's maximum isometric force, $R_{m,j}$ is the muscle's moment arm, τ_j is the generalized force (torque) around the jth joint, and p is a user defined constant. External load was applied as the ground reaction force files extracted using the toolbox (

Figure **9**). The analysis tool was also used to calculate muscle moment arms.

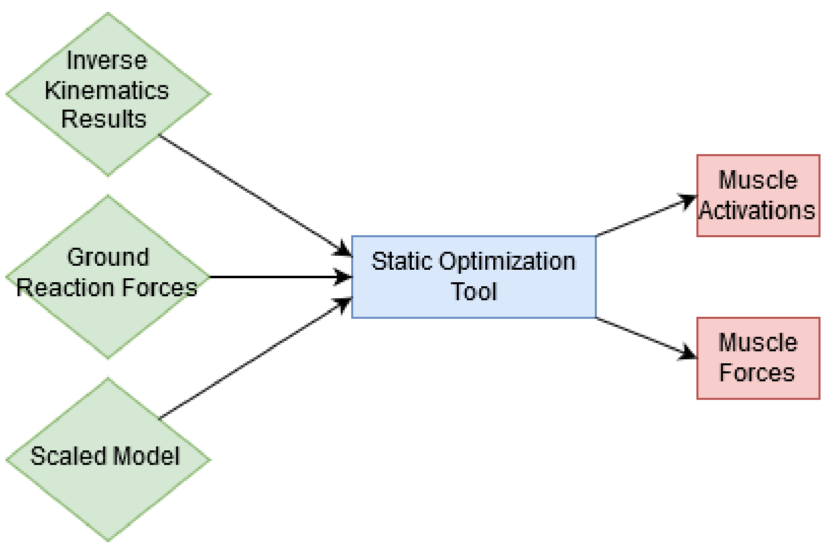


Figure 9. Inputs and outputs of the OpenSim static optimization tool.

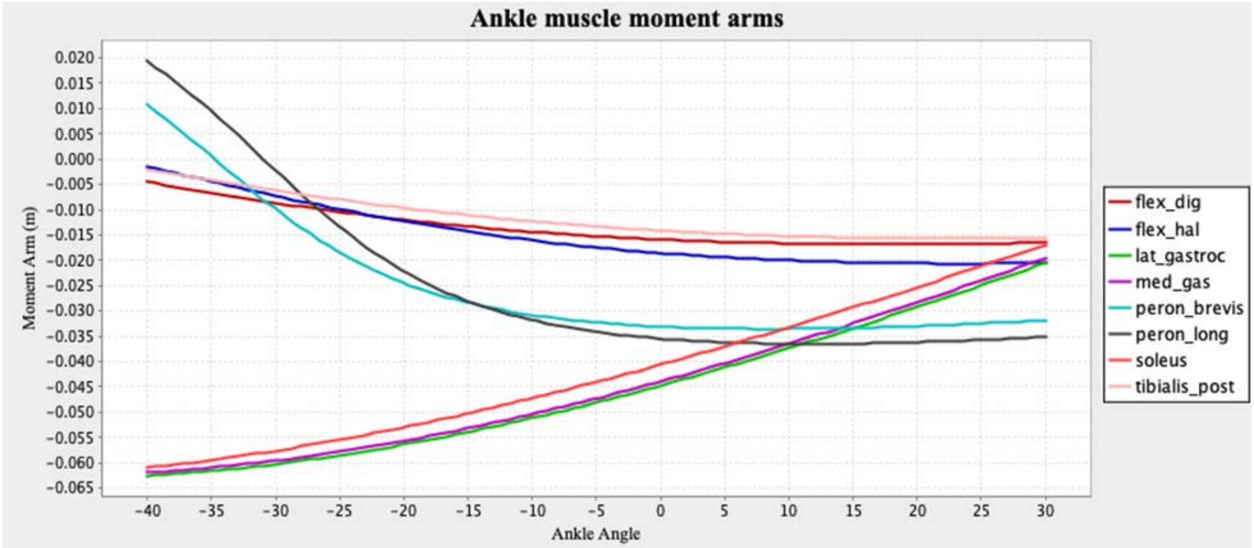


Figure 10. Example moment arm output for subject 1.

Statistical Analysis

There were two groups (younger: 8-14 years and older: 15-17 years), and two time points (pre- and post-run conditions). The model contained 86 muscle actuators. Since the model separates certain muscles (for example the gluteal minimums, medius and maximus are each composed of 3 actuators), these were summed together for the purposes of this analysis. The primary muscles of interest were the main hip and knee flexors and extensors, as well as the main ankle dorsiflexors and plantarflexors, although all muscles were submitted for analysis. All forces were also normalized by body weight. Differences were tested using a two-way (2 group x 2 time) mixed analysis of variance with one within-subjects factor (time) and one between-subjects factor (group). The significance level was set at $\alpha = 0.05$. SPSS 22 (IBM Corp., Armonk, NY) was used to conduct statistical analysis.

Results

In the multivariate analysis, there was a significant difference in muscle forces pre and post run ($F(1,7) = 13658.99$, $p = 0.007$). There was also a significant interaction between the age level of the runner and how muscle activity changed pre and post run ($F(1,7) = 3399.77$, $p = 0.013$).

Fatigue

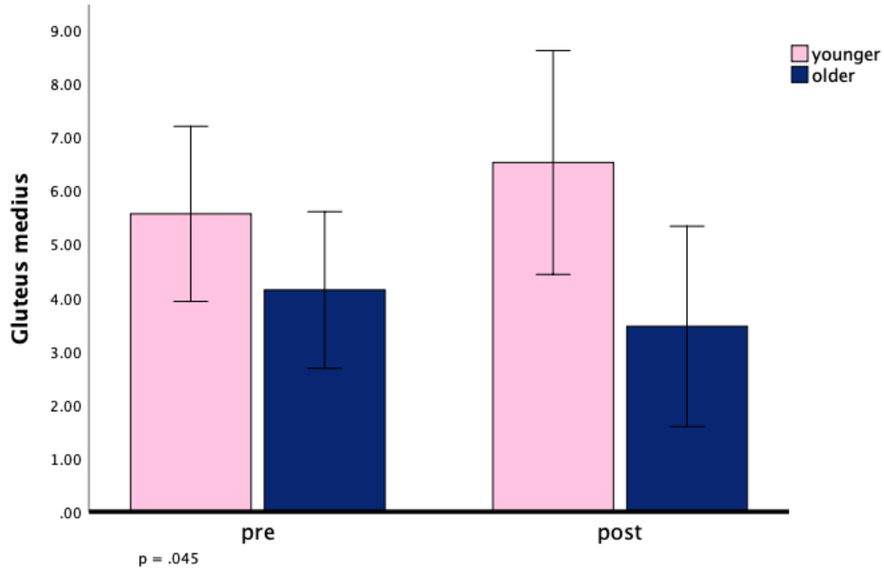
The largest changes before and after the run were exhibited at the knee joint. While the biceps femoris force was significantly greater post-run, the quadriceps force decreased, along with the pectineus muscle (Table 5).

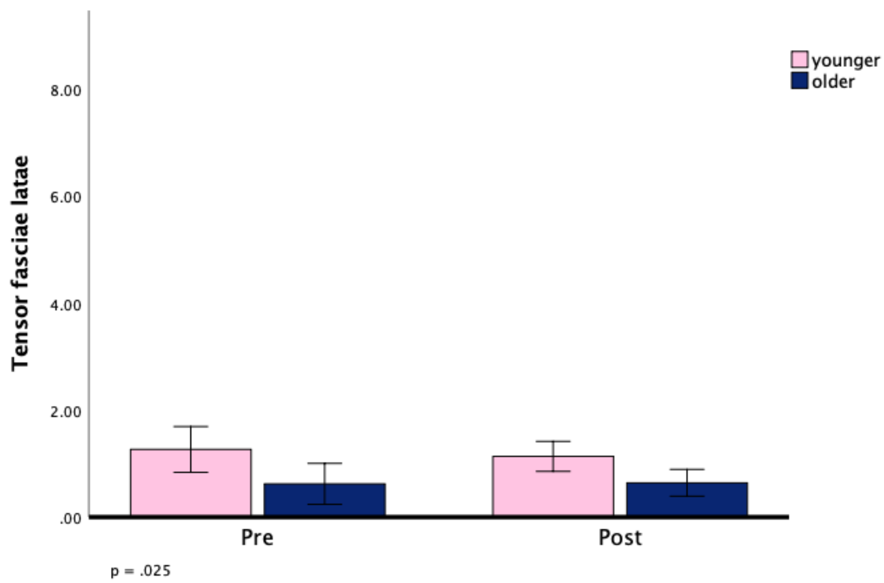
Table 6. Significant muscle forces pre and post run (SD)

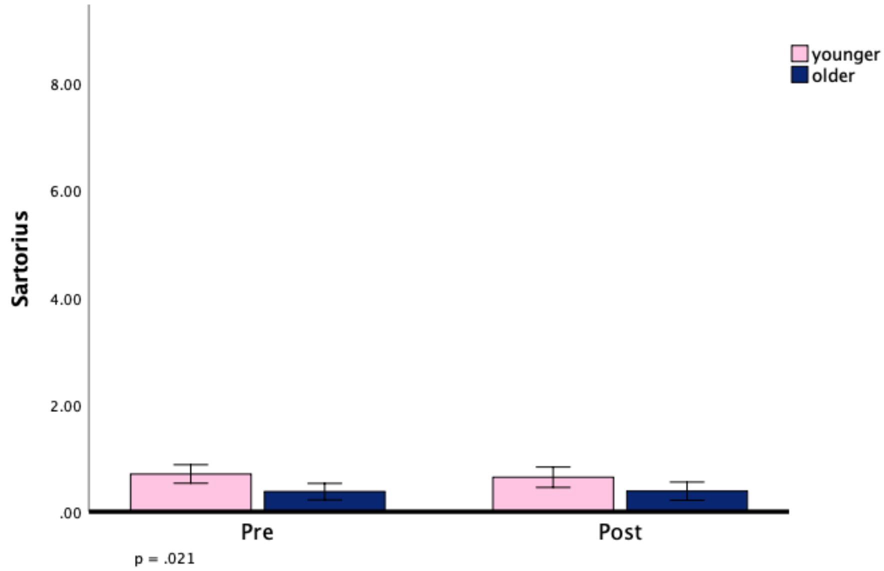
Muscle	Pre	Post	F	P
Biceps Femoris (BW)	1.82 (1.02)	3.60 (1.71)	17.610	0.004
Quadriceps (BW)	1.34 (.86)	1.17 (.83)	12.090	0.010
Pectineus (BW)	.80 (.38)	.63 (.18)	9.065	0.020

Age level

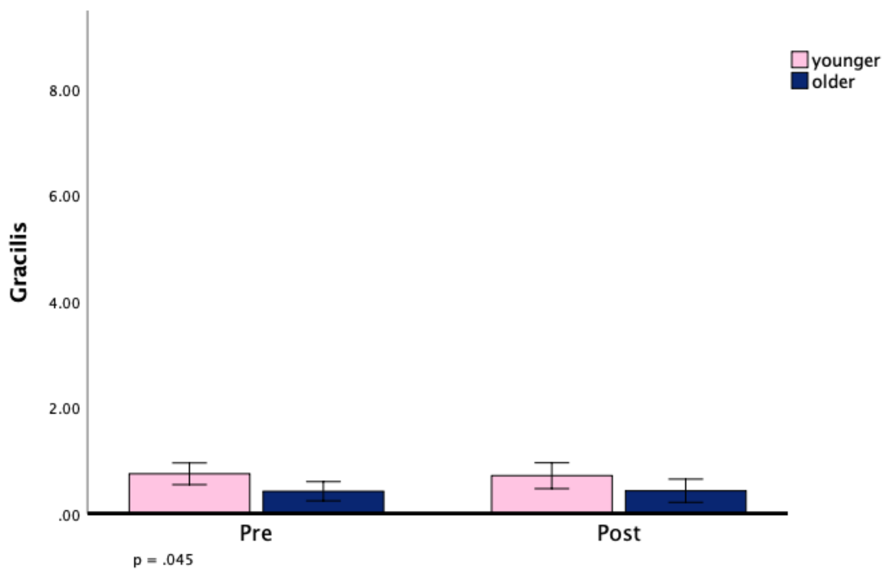
Fatigue affected the two age levels quite differently pre and post run. Muscles most significantly affected include the gluteus medius and minimus, the sartorius, tensor fasciae latae, gracilis, flexor digitorum, peroneus brevis and longus, and extensor digitorum and hallucis longus. Comparisons of the significant pre and post maximum muscle forces for each group are depicted below, in multiples of bodyweight.


9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
.00
Gluteus medius
younger
older
pre
post
p = .045

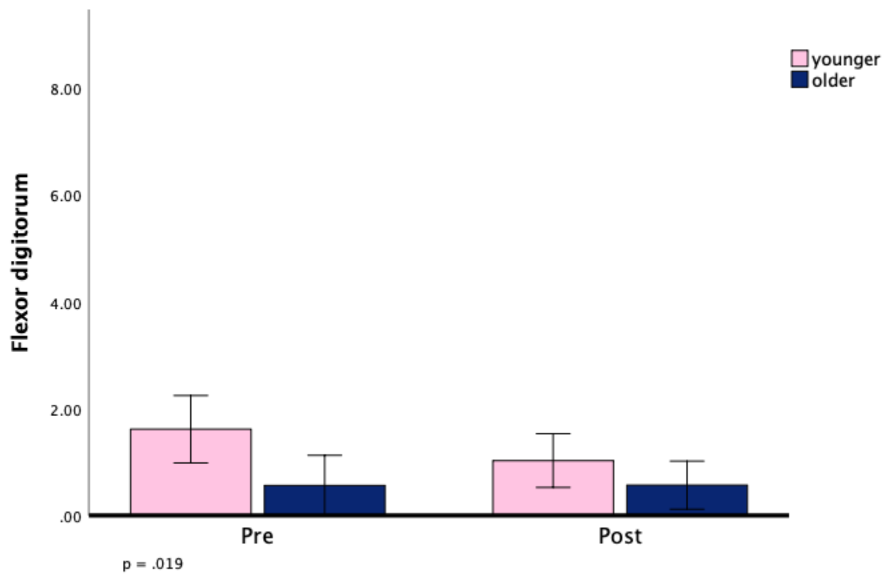

8.00
6.00
4.00
2.00
.00
Tensor fasciae latae
younger
older
Pre
Post
p = .025

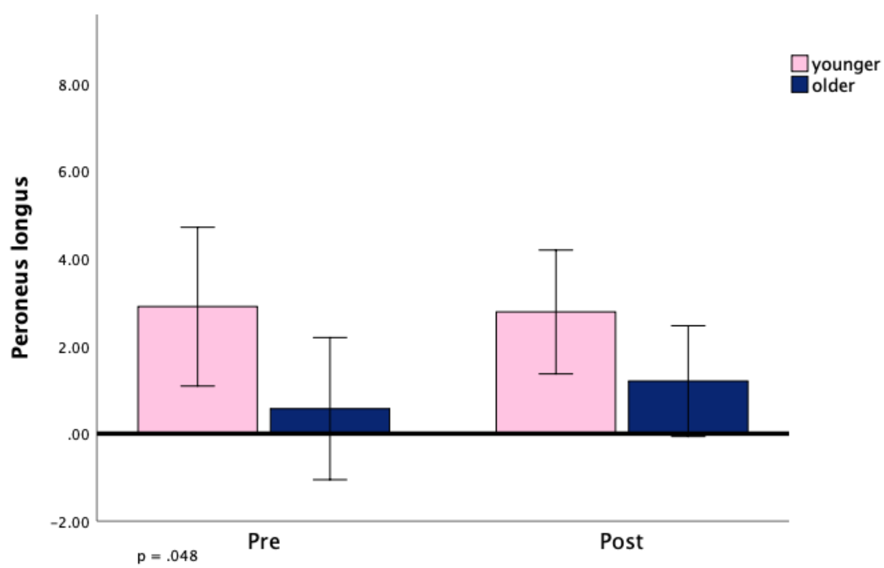


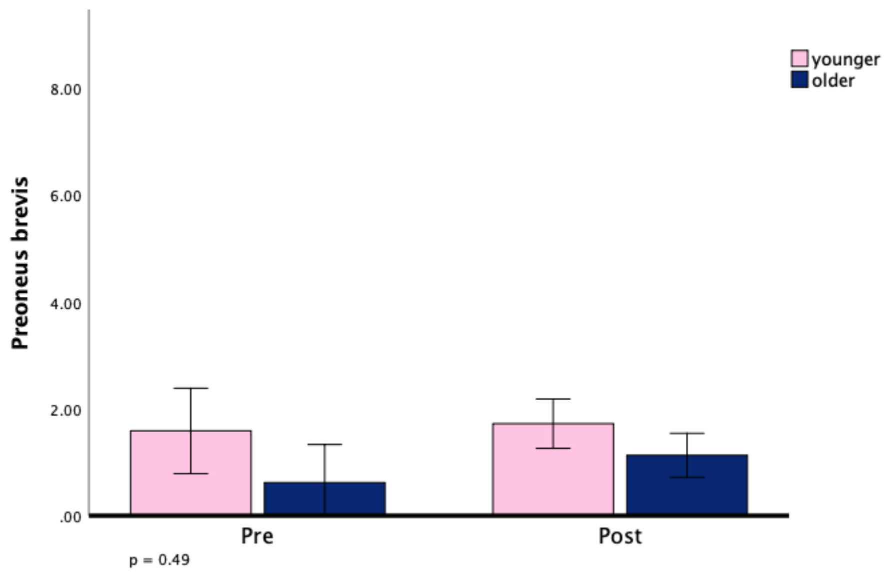
younger
older
8.00
6.00
Sartorius
4.00
2.00
.00
Pre
Post
p = .021

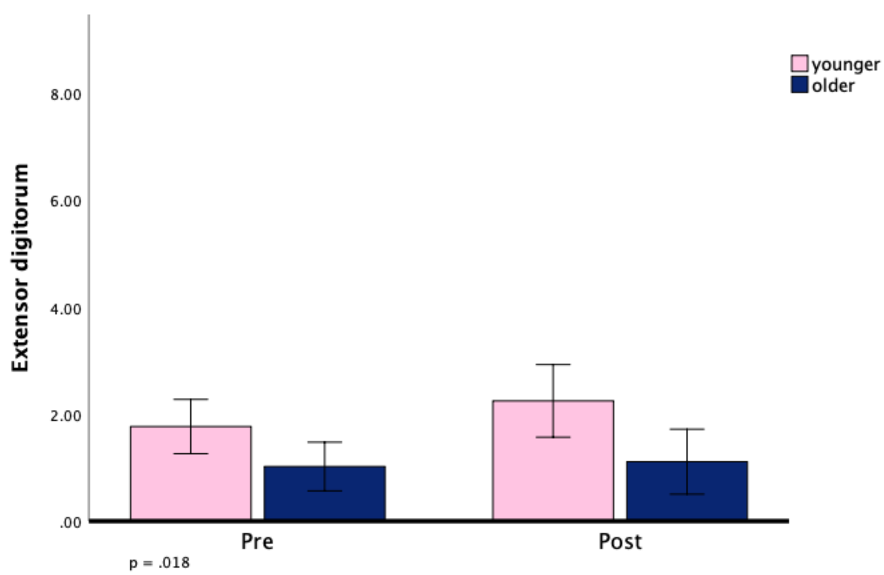


younger
older
8.00
6.00
Gracilis
4.00
2.00
.00
Pre
Post
p = .045


younger
older
8.00
6.00
4.00
2.00
.00
Flexor digitorum
Pre
Post
p = .019


younger
older
8.00
6.00
4.00
2.00
.00
-2.00
Peroneus longus
Pre
Post
p = .048


younger
older
8.00
6.00
4.00
2.00
.00
Preoneus brevis
Pre
Post
p = 0.49


younger
older
8.00
6.00
4.00
2.00
.00
Extensor digitorum
Pre
Post
p = .018

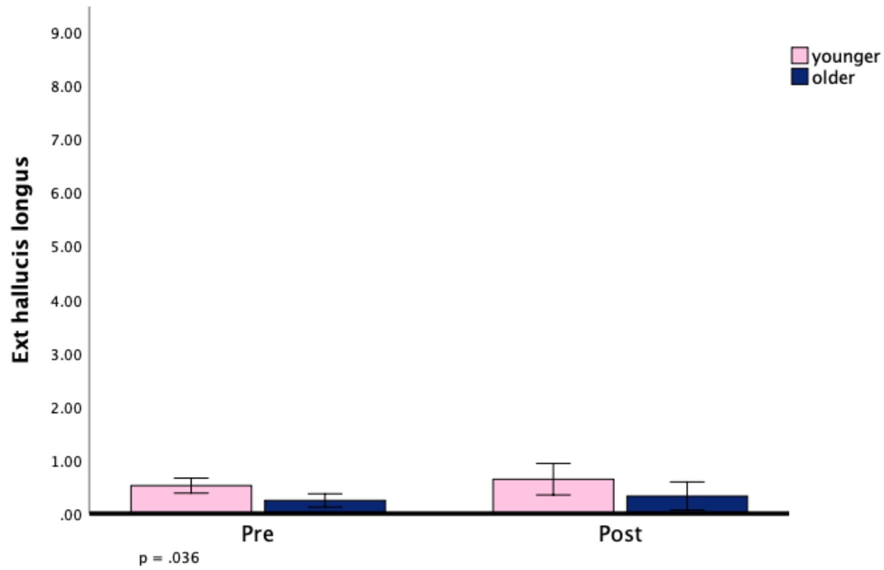


Figure 11. Estimated muscle forces with significant age differences (in times bodyweight).

Regression Analysis

Simple regression analysis to predict normalized force based on age was found to be statistically significant for a number of muscles, including the TFL ($F(1,8) = 81.28$, $p < 0.001$), quadriceps femoris ($F(1,8) = 24.43$, $p = 0.001$), rectus femoris ($F(1,8) = 78.92$, $p < 0.001$), and tibialis anterior ($F(1,8) = 35.27$, $p < 0.001$), with a 16%, 26%, 52%, and 63% decrease respectively with each passing year. This approach could be clarifying in future studies with multiple subjects for each age to minimize the influence of potential outliers.

Discussion

Results from the same group in Chapter 2 did not show large differences in kinematics or peak ground reaction forces before and after a five-kilometer run. However, there were some notable age-related differences in kinetics, particularly at the knee. Older runners exhibited greater amounts of power generation and absorption, as well as a higher moment. However, the post-run results counter the hypothesis. Changes in the normalized quadriceps forces and the biceps femoris forces decreased and increased respectively for both age groups, not differentially as one would assume, given the connected data and the fact that force generation capabilities become more developed with maturity. The inverse change for knee flexion and extension is troubling for potential imbalance around the knee joint and for the onset of patellofemoral pain. This suggests all age groups would benefit from quadriceps strengthening exercises, or cross training and off-season activities such as biking.

For the differences in muscle forces between the age groups, there are three main aspects of concern. First, the younger group was found to be operating at higher muscle forces relative to their body weight, potentially increasing stresses on the joints as well as the tendons, putting them at higher risk of overuse injuries. In the future, isolating adolescent runners may be prudent given their unique set of risk factors. For instance, there is evidence that all biological tissues do not grow and change at the same time or at the same rate – for example strength increasing by a larger factor than the cross sectional area of its associated tendon (Hawkins & Metheny, 2001). Studies of muscle activity in children during walking and running indicates that levels of co-contraction are negatively related to age, suggesting that some of the higher muscle forces may simply be due to higher levels of co-contraction in the younger age group (Frost et al., 1997).

The decrease in tensor fascia latae force and apparent compensation by the gluteus medius and minimus muscles both occurred just prior to foot contact. These changes may place the younger group at higher risk for iliotibial band syndrome, which is the most common running injury of the lateral knee (Lavine, 2010) and the cause of 7% of female high school running injuries (Tenforde et al., 2011). Prevention strategies in this group could include stretching and/or hip strengthening exercises.

Similarly, there is a change in the overall balance at the ankle towards the dorsiflexors and away from the plantarflexors. This can lead to repeated bending of the tibia, aggravated over longer periods with higher running volume. In addition, if development of the tendons happens to lag behind growth of the tibia, the relevant musculotendon units are now acting from a stretched resting position, which has been documented at the quadriceps femoris in late adolescent males (Charcharis et al., 2019). These factors would further increase tensile forces that can contribute to mid and distal tibial stress fractures. In addition, this ankle imbalance has been associated with increased shank acceleration and impact, adding to the potential accumulation of stress in the area (J. Mizrahi et al., 2000).

Limitations

As this was a simulation, results could have been checked against EMG recordings, however, the results are within range of studies measuring activity in adult runners (Dorn et al., 2012). This study could have also benefited from a larger subject base, since there seemed to be a fair amount of variability, particularly in the younger subject group. Future studies could also investigate the effects of altering the length of the muscle-tendon unit to mimic growth conditions and investigating its effects using forward dynamics. Future results can be further refined by obtaining individual-specific maximal muscle forces, as has been done in studies performing simulations of children with cerebral palsy (Hegarty et al., 2019).

Since static optimization considers each instant in time individually, it doesn’t account for the anticipatory muscle activations that may occur during running. In addition, the model can potentially overestimate the baseline level excitations of larger muscles and underestimating those of smaller muscles, however, the muscles examined in this study are on a relatively similar scale, and despite the listed limitations in this simulation approach, this study provides meaningful initial insights into the muscular strategies of growing female athletes that can be further studied and validated, possibly with EMG data.

Conclusion

Overall, evidence from this study points to the idea that younger runners may especially benefit from hip and ankle strengthening exercises to avoid imbalances that may predispose them to injury. In addition, due to the repetitive and high-volume nature of distance running, young and adolescent runners may especially benefit from de-loading periods and more gradual increases in weekly and monthly running volume. Based on the simulation results which are currently the first estimates of how different age runners handle fatigue differently on a muscular level, they may also benefit from more careful monitoring of their running load.

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APPENDICES

Appendix A

Appendix A.1

Table 7. Descriptive statistics for spatiotemporal, kinematic, and kinetic variables.

	Age	Mean	Std. Deviation	N
PreCad	older	172.56	4.98	6
	younger	184.13	11.27	5
	Total	177.82	9.99	11
PostCad	older	171.67	3.69	6
	younger	171.33	22.39	5
	Total	171.51	14.40	11
PreStride	older	2.31	.27	6
	younger	2.09	.25	5
	Total	2.21	.27	11
PostStride	older	2.32	.25	6
	younger	2.07	.39	5
	Total	2.21	.33	11
Pre_GRF	older	2.43	.19	6
	younger	2.47	.11	5
	Total	2.45	.15	11
Post_GRF	older	2.33	.31	6
	younger	2.50	.15	5
	Total	2.40	.26	11
Pre_K_Flex	older	94.10	23.64	6
	younger	102.33	9.85	5
	Total	97.84	18.35	11
Post_K_Flex	older	98.81	15.34	6
	younger	106.41	13.34	5
	Total	102.26	14.30	11
Pre_M	older	3.44	.63	6
	younger	2.70	.62	5
	Total	3.10	.71	11
Post_M	older	3.44	.88	6

	younger	2.51	.40	5
	Total	3.02	.83	11
Pre_PG	older	11.21	4.11	6
	younger	7.89	2.23	5
	Total	9.70	3.66	11
Post_PG	older	11.29	2.99	6
	younger	7.67	2.56	5
	Total	9.64	3.27	11
Pre_PA	older	14.40	1.41	6
	younger	11.25	3.70	5
	Total	12.97	3.03	11
Post_PA	older	15.09	4.19	6
	younger	10.99	4.01	5
	Total	13.23	4.45	11
Pre_Dorsi	older	31.71	4.09	6
	younger	27.73	7.98	5
	Total	29.90	6.18	11

Table 8. Within subjects analysis of variance results

		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
time	cadence	255.800	1	255.800	1.184	.305	.116
	stridel	0.000054	1	0.000054	.005	.946	.001
	GRF	.008	1	.008	1.049	.333	.104
	Knee_Flex	105.160	1	105.160	2.039	.187	.185
	Knee_M	.049	1	.049	.565	.471	.059
	Knee_PG	.026	1	.026	.013	.912	.001
	Knee_PA	.251	1	.251	.040	.846	.004
	Ankle_DF	158.992	1	158.992	1.205	.301	.118
	Ankle_Pf	2861.334	1	2861.334	3.275	.104	.267
	Ankle_int	26.481	1	26.481	1.019	.339	.102
	Ankle_ext	12.242	1	12.242	.511	.493	.054
	Ankle_M	.172	1	.172	4.157	.072	.316
	Ankle_P	7.744	1	7.744	4.708	.058	.343
	Hip_flex	.298	1	.298	.014	.908	.002
	Hip_ext	7.895	1	7.895	1.011	.341	.101

	Hip_add	4.155	1	4.155	.395	.545	.042
	Hip_abd	22.502	1	22.502	2.375	.158	.209
	Hip_M	.130	1	.130	4.259	.069	.321
	Hip_P	.010	1	.010	.006	.938	.001

Table 9. Between subjects analysis of variance results

		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	cadence	172.190	1	172.190	2.039	.187	.185
	stride	.304	1	.304	1.932	.198	.177
	GRF	.060	1	.060	.742	.411	.076
	Knee_Flex	342.024	1	342.024	.668	.435	.069
	Knee_M	3.824	1	3.824	4.715	.058	.344
	Knee_PG	65.604	1	65.604	3.756	.085	.294
	Knee_PA	71.510	1	71.510	3.997	.077	.308
	Ankle_DF	31.966	1	31.966	.322	.584	.035
	Ankle_Pf	1738.742	1	1738.742	1.291	.285	.125
	Ankle_int	401.580	1	401.580	1.322	.280	.128
	Ankle_ext	1892.695	1	1892.695	5.062	.051	.360
	Ankle_M	.117	1	.117	.392	.547	.042
	Ankle_P	6.953	1	6.953	.444	.522	.047
	Hip_flex	3.505	1	3.505	.035	.856	.004
	Hip_ext	76.074	1	76.074	.846	.382	.086
	Hip_add	6.681	1	6.681	.357	.565	.038
	Hip_abd	98.281	1	98.281	4.687	.059	.342
	Hip_M	.401	1	.401	1.422	.264	.136
	Hip_P	.008	1	.008	.001	.976	.000

Appendix A.2

Figure 12. Means and standard deviations for maximum muscle forces for young and older runners, and the group as a whole.

Muscle	Group	Mean	SD	N
glut_med	younger	5.56	1.72	4
	older	4.14	1.06	5
	Total	4.77	1.50	9
Post_glut_med	younger	6.52	2.66	4
	older	3.46	.42	5
	Total	4.82	2.31	9
glut_min	younger	3.35	.62	4
	older	2.07	.31	5
	Total	2.64	.80	9
post_glut_min	younger	2.74	1.06	4
	older	1.73	.31	5
	Total	2.18	.87	9
semimem_r	younger	2.37	2.60	4
	older	1.69	.58	5
	Total	1.99	1.68	9
post_semimem_r	younger	2.67	1.66	4
	older	1.80	.47	5
	Total	2.19	1.16	9
semiten_r	younger	1.18	.43	4
	older	.70	.22	5
	Total	.91	.40	9
post_semiten_r	younger	1.13	.28	4
	older	1.01	.16	5
	Total	1.06	.21	9
bifem	younger	2.49	1.28	4
	older	1.28	.16	5
	Total	1.82	1.02	9
post_bifem	younger	4.36	2.23	4
	older	3.00	1.02	5
	Total	3.61	1.71	9
sar_r	younger	.70	.22	4
	older	.37	.03	5
	Total	.52	.22	9
post_sar_r	younger	.64	.24	4

	older	.38	.03	5
	Total	.50	.20	9
add_long_r	younger	1.25	.30	4
	older	1.21	.27	5
	Total	1.23	.27	9
post_add_long_r	younger	1.13	.35	4
	older	1.30	.46	5
	Total	1.23	.40	9
add_brev_r	younger	1.58	.97	4
	older	.58	.28	5
	Total	1.02	.82	9
post_add_brev_r	younger	.99	.32	4
	older	.88	.17	5
	Total	.93	.24	9
add_mag	younger	4.40	2.98	4
	older	2.12	.70	5
	Total	3.13	2.24	9
post_add_mag	younger	3.10	1.13	4
	older	2.03	.28	5
	Total	2.51	.92	9
tfl_r	younger	1.27	.55	4
	older	.62	.06	5
	Total	.91	.48	9
post_tfl_r	younger	1.14	.36	4
	older	.64	.04	5
	Total	.86	.34	9
pect_r	younger	1.07	.45	4
	older	.58	.12	5
	Total	.80	.38	9
post_pect_r	younger	.74	.23	4
	older	.54	.07	5
	Total	.63	.18	9
grac_r	younger	.75	.26	4
	older	.42	.02	5
	Total	.57	.24	9
post_grac_r	younger	.72	.31	4
	older	.43	.03	5

	Total	.56	.24	9
glut_max	younger	5.44	3.03	4
	older	3.03	.67	5
	Total	4.10	2.30	9
post_glut_Max	younger	5.72	3.46	4
	older	3.67	1.02	5
	Total	4.58	2.49	9
iliacus_r	younger	3.70	.77	4
	older	2.60	.40	5
	Total	3.09	.80	9
post_iliacus_r	younger	3.84	1.71	4
	older	2.54	.42	5
	Total	3.12	1.29	9
psoas_r	younger	4.24	1.79	4
	older	3.16	.36	5
	Total	3.64	1.26	9
post_psoas_r	younger	4.02	1.38	4
	older	2.80	.46	5
	Total	3.34	1.11	9
quad_fem_r	younger	1.81	1.19	4
	older	.97	.13	5
	Total	1.34	.86	9
post_quad_fem_r	younger	1.50	1.25	4
	older	.91	.15	5
	Total	1.17	.83	9
rect_fem_r	younger	5.15	1.89	4
	older	3.22	.16	5
	Total	4.08	1.54	9
post_rect_fem_r	younger	4.54	2.59	4
	older	3.09	.31	5
	Total	3.74	1.77	9
vas_med_r	younger	4.42	3.51	4
	older	2.44	.94	5
	Total	3.32	2.48	9
post_vas_med_r	younger	1.65	.90	4
	older	2.50	.98	5
	Total	2.12	.99	9

vas_lat_r	younger	2.53	2.54	4
	older	1.76	.87	5
	Total	2.10	1.72	9
post_vas_lat_r	younger	1.41	1.12	4
	older	1.36	.64	5
	Total	1.38	.82	9
vas_int_r	younger	2.85	2.81	4
	older	1.50	.44	5
	Total	2.10	1.89	9
post_vas_int_r	younger	1.21	.75	4
	older	1.93	.93	5
	Total	1.61	.89	9
gas	younger	4.90	4.73	4
	older	1.76	.93	5
	Total	3.15	3.40	9
post_gas	younger	5.48	5.34	4
	older	2.02	1.05	5
	Total	3.56	3.81	9
soleus_r	younger	7.01	6.60	4
	older	1.25	1.05	5
	Total	3.81	5.11	9
post_soleus_r	younger	3.06	2.21	4
	older	1.54	1.57	5
	Total	2.22	1.93	9
tib_post_r	younger	5.05	5.13	4
	older	.61	.38	5
	Total	2.59	3.92	9
post_tib_post_r	younger	3.11	2.50	4
	older	1.58	.65	5
	Total	2.26	1.79	9
flex_dig_r	younger	1.61	.78	4
	older	.56	.21	5
	Total	1.03	.75	9
post_flex_dig_r	younger	1.03	.56	4
	older	.57	.28	5
	Total	.77	.47	9
flex_hal_r	younger	.95	1.04	4

	older	.28	.14	5
	Total	.58	.73	9
post_flex_hal_r	younger	.66	.37	4
	older	.32	.09	5
	Total	.47	.30	9
tib_ant_r	younger	3.75	2.70	4
	older	1.60	.27	5
	Total	2.56	2.01	9
post_tib_ant_r	younger	2.90	.93	4
	older	1.68	.17	5
	Total	2.22	.87	9
per_brev_r	younger	1.59	.97	4
	older	.62	.31	5
	Total	1.05	.81	9
post_per_brev_r	younger	1.72	.59	4
	older	1.13	.09	5
	Total	1.39	.48	9
per_long_r	younger	2.90	2.28	4
	older	.57	.49	5
	Total	1.61	1.89	9
post_per_long_r	younger	2.78	1.77	4
	older	1.20	.40	5
	Total	1.90	1.40	9
ext_dig_r	younger	1.77	.52	4
	older	1.02	.34	5
	Total	1.35	.56	9
post_ext_dig_r	younger	2.25	.85	4
	older	1.11	.18	5
	Total	1.62	.80	9
ext_hal_r	younger	.52	.14	4
	older	.25	.09	5
	Total	.37	.18	9
post_ext_hal_r	younger	.64	.37	4
	older	.33	.07	5
	Total	.47	.29	9

Table 10. Within subjects muscle force analysis results

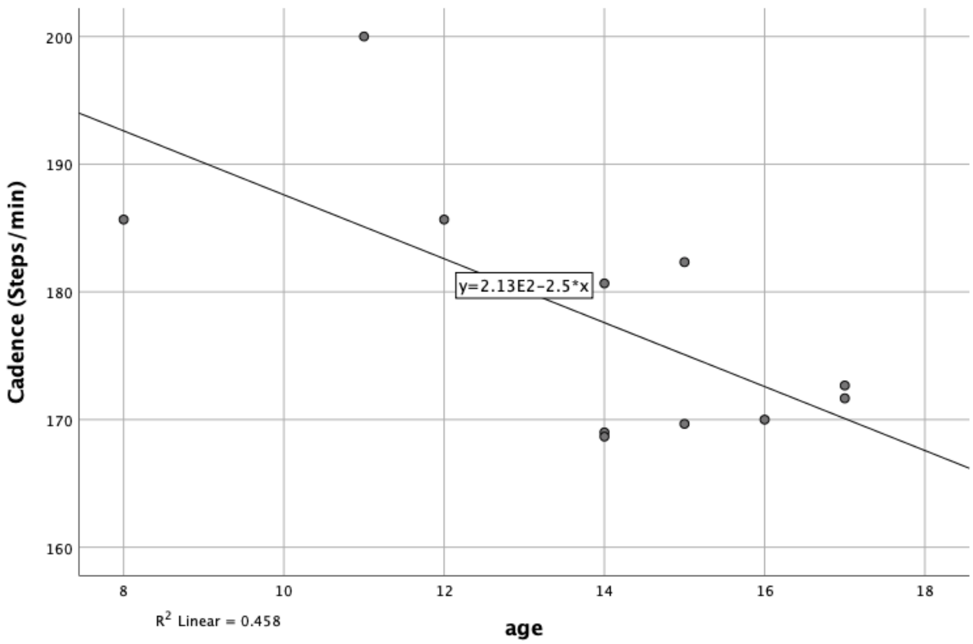
	Muscle	Sum of Squares	df	Mean Square	F	Sig	Partial Eta Squared
time	glutmed	.086	1	.086	.069	.801	.010
	glumin	1.015	1	1.015	3.915	.088	.359
	semimem	.193	1	.193	.218	.655	.030
	semiten	.077	1	.077	1.401	.275	.167
	bi_fem	14.294	1	14.294	17.610	.004	.716
	sar	.003	1	.003	1.149	.319	.141
	add_long	.001	1	.001	.015	.905	.002
	add_brev	.094	1	.094	.689	.434	.090
	addmagn	2.143	1	2.143	2.228	.179	.241
	tfl	.013	1	.013	1.494	.261	.176
	pect	.149	1	.149	9.065	.020	.564
	grac	.001	1	.001	.540	.486	.072
	glutmax	.949	1	.949	2.100	.191	.231
	illi	.007	1	.007	.012	.917	.002
	psoas	.375	1	.375	1.754	.227	.200
	quad	.149	1	.149	12.090	.010	.633
	rec_fem	.609	1	.609	3.123	.121	.308
	vas_med	8.115	1	8.115	4.486	.072	.391
	vas_lat	2.575	1	2.575	3.651	.098	.343
	vas_int	1.645	1	1.645	1.246	.301	.151
	gastr	.789	1	.789	.115	.744	.016
	soleus	14.793	1	14.793	2.106	.190	.231
	tib_post	1.054	1	1.054	.217	.656	.030
	flex_digi	.376	1	.376	1.991	.201	.221
	flex_hal	.070	1	.070	.263	.624	.036
	tib_ant	.660	1	.660	.862	.384	.110
	perv_brev	.468	1	.468	3.664	.097	.344
	per_long	.286	1	.286	.349	.573	.048
	ext_dig	.360	1	.360	3.872	.090	.356
	ext_hal	.045	1	.045	2.476	.160	.261

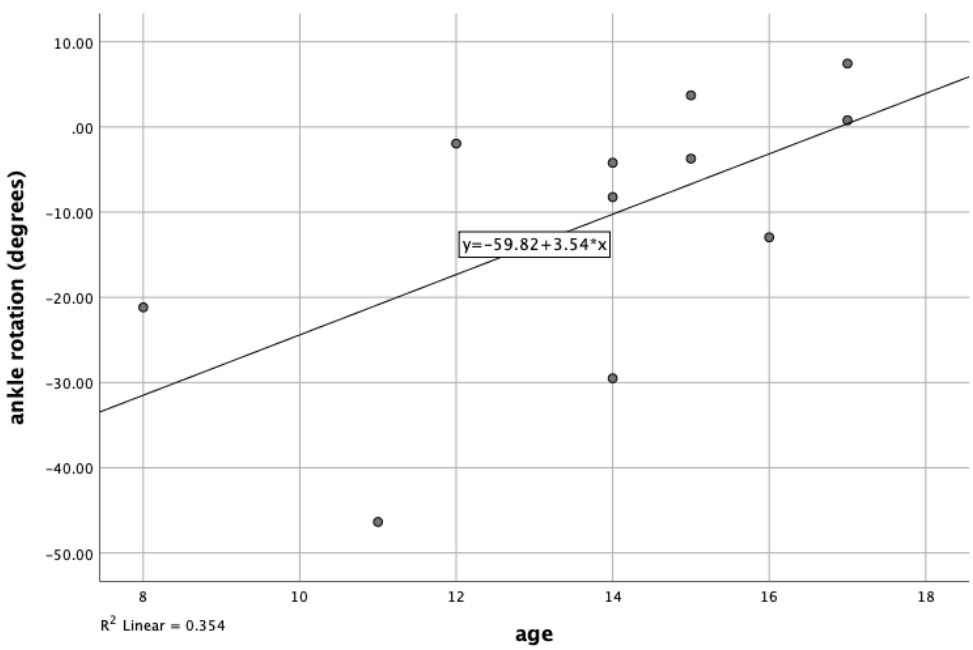
Table 11. Between subjects muscle force analysis results

Muscle	Sum of Squares	df	Mean Square	F	Sig	Partial Eta Squared
glutmed	22.341	1	22.341	5.904	.045	.458
glumin	5.820	1	5.820	11.748	.011	.627
semimem	2.645	1	2.645	.755	.414	.097
semiten	.421	1	.421	4.326	.076	.382
bi_fem	7.379	1	7.379	2.796	.138	.285
sar	.385	1	.385	8.697	.021	.554
add_long	.021	1	.021	.101	.760	.014
add_brev	1.397	1	1.397	3.729	.095	.348
addmagn	12.490	1	12.490	3.367	.109	.325
tfl	1.439	1	1.439	8.059	.025	.535
pect	.521	1	.521	5.086	.059	.421
grac	.416	1	.416	5.902	.045	.457
glutmax	22.062	1	22.062	2.329	.171	.250
illi	6.413	1	6.413	5.799	.047	.453
psoas	5.883	1	5.883	2.711	.144	.279
quad	2.262	1	2.262	1.748	.228	.200
rec_fem	12.612	1	12.612	2.943	.130	.296
vas_med	1.415	1	1.415	.290	.607	.040
vas_lat	.775	1	.775	.237	.641	.033
vas_int	.444	1	.444	.152	.708	.021
gastr	48.350	1	48.350	3.009	.126	.301
soleus	58.880	1	58.880	3.732	.095	.348
tib_post	39.494	1	39.494	4.202	.080	.375
flex_digi	2.548	1	2.548	9.181	.019	.567
flex_hal	1.134	1	1.134	4.181	.080	.374
tib_ant	12.684	1	12.684	4.565	.070	.395
perv_brev	2.707	1	2.707	5.631	.049	.446
per_long	16.991	1	16.991	5.717	.048	.450
ext_dig	3.943	1	3.943	9.360	.018	.572
ext_hal	.389	1	.389	6.720	.036	.490

Appendix B

Appendix B.1


Cadence (Steps/min)
200
190
180
170
160
y=2.13E2-2.5*x
8
10
12
14
16
18
R2 Linear = 0.458
age


ankle rotation (degrees)
10.00
.00
-10.00
-20.00
-30.00
-40.00
-50.00
y=-59.82+3.54*x
8
10
12
14
16
18
R2 Linear = 0.354
age

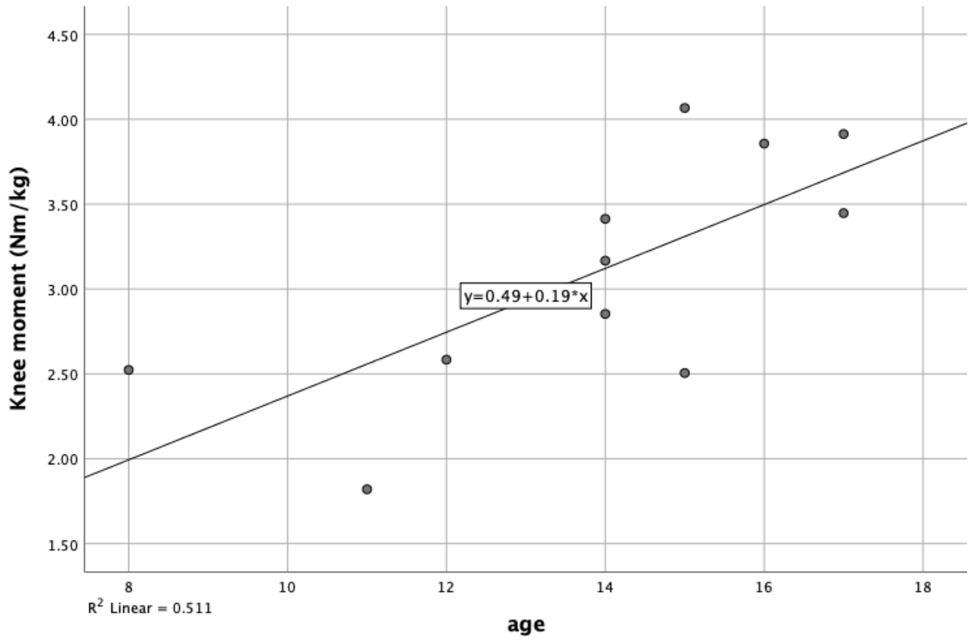
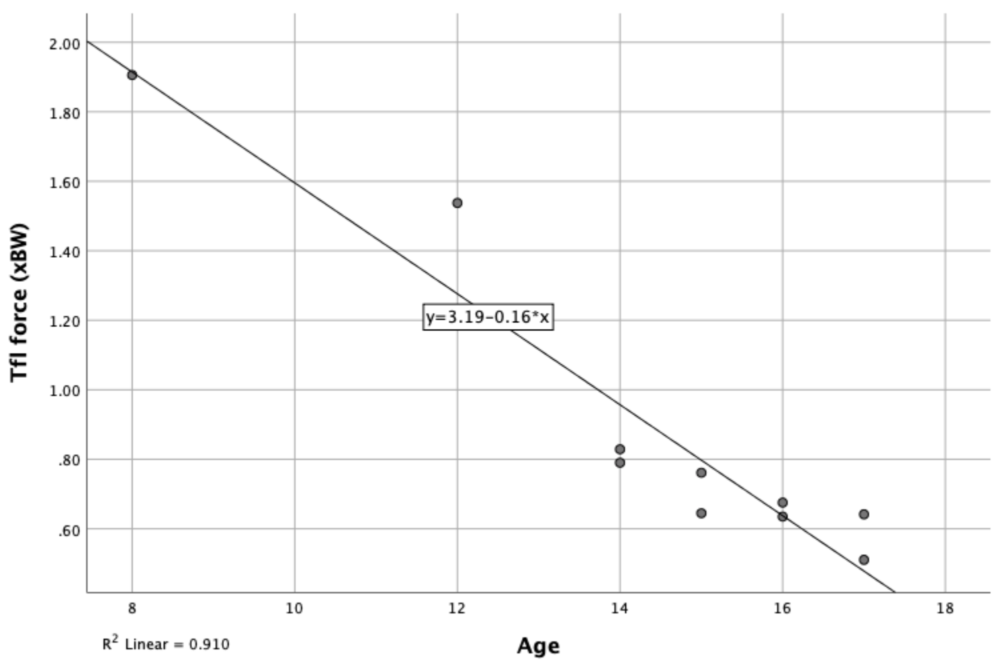
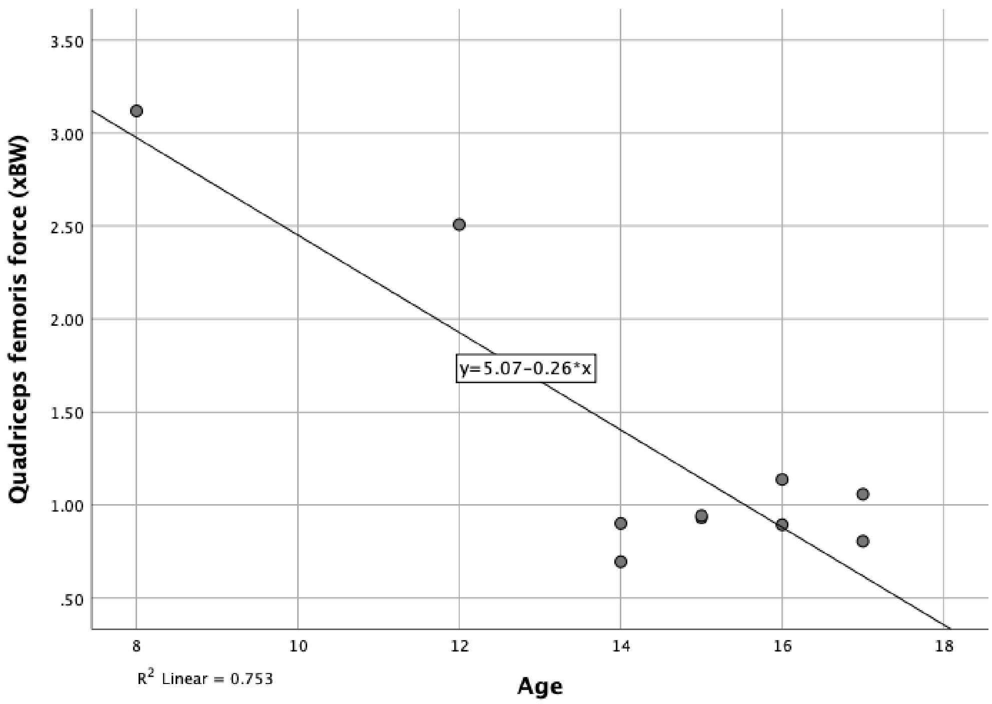
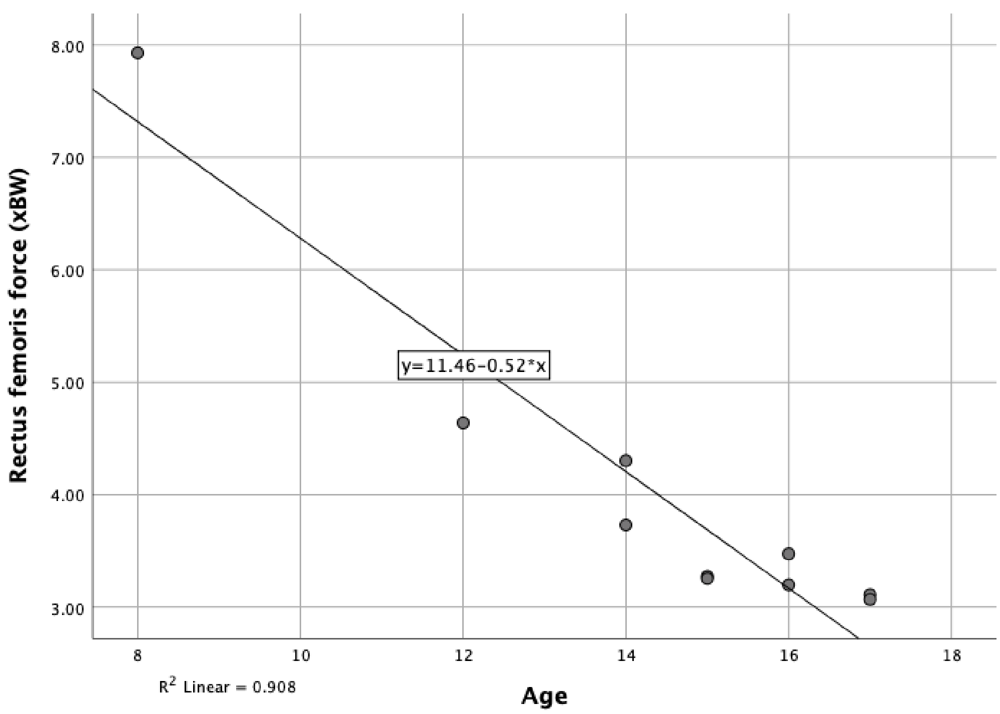


Figure 13. Linear regressions for cadence, ankle rotation, and knee moment on age.

Appendix B.2




3.50
3.00
2.50
2.00
1.50
1.00
.50
Quadriceps femoris force (xBW)
y=5.07-0.26*x
8
10
12
14
16
18
R2 Linear = 0.753
Age


8.00
7.00
6.00
5.00
4.00
3.00
Rectus femoris force (xBW)
y=11.46-0.52*x
8
10
12
14
16
18
R2 Linear = 0.908
Age

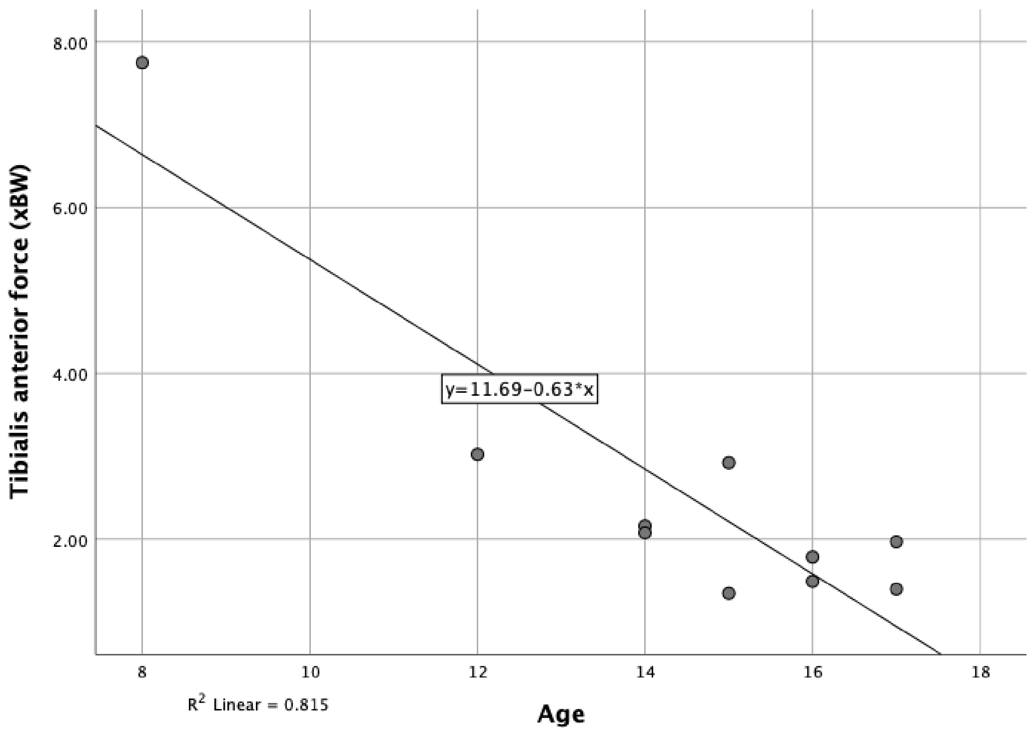


Figure 14. Linear regressions for normalized tensor fasciae latae, quadriceps femoris, rectus femoris, and tibialis anterior forces on age.