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THE EFFECTS OF MOVEMENT COMPLEXITY ON RELATIONSHIPS AMONG FOOT ANTHROPOMETRY AND JUMP PERFORMANCE

A Thesis
by
DAVID SCHUMACHER

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May 2020

APPROVED BY:

Herman van Werkhoven, Ph.D.
Chairperson, Thesis Committee

Alan R. Needle, Ph.D.
Member, Thesis Committee

Jennifer S. Howard, Ph.D.
Member, Thesis Committee

Kelly J. Cole, Ph.D.
Chairperson, Department of Health and Exercise Science

Mike McKenzie, Ph.D.
Dean, Cratis D. Williams School of Graduate Studies

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Abstract

THE EFFECTS OF MOVEMENT COMPLEXITY ON RELATIONSHIPS AMONG FOOT ANTHROPOMETRY AND JUMP PERFORMANCE

David Schumacher
B.S., Oregon State University
M.S., Appalachian State University

Chairperson: Herman van Werkhoven

Previous research has attempted to link performance in powerful movements, such as jumping and sprinting, to foot anthropometry. However, results are often inconsistent, potentially due to different movement types being used in various experimental and modeling approaches. It is currently not known whether changing the complexity of a jump from single joint (foot and ankle only) to multi-joint jump (whole lower leg) affects relationships between anthropometry and performance. The purpose of this study was to investigate possible relationships between foot anthropometric measures and jump performance and whether movement complexity influences these relationships. Forty participants (20 men and 20 women; age: 22 ± 2.5 y; height: 172.3 ± 10.3 cm; body mass: 75.3 ± 15.1 kg) performed jumps with the right leg only on an inclined sled. The participants performed: 1) ankle jumps with (ACMJ) and without (ASJ) a countermovement, and 2) whole lower extremity jumps with (CMJ) and without (SJ) a countermovement. Each jump was repeated twice while peak jump height was recorded. Dual energy x-ray absorptiometry (DEXA) scans of each participant's right foot were used to measure Achilles tendon moment arm (ATMA), metatarsal length and hallux length. Arch stiffness was calculated using foot measures taken from photographic images. Relationships between anthropometric measures and jump performances were tested using Pearson product-moment correlations. A Fisher exact test was performed to determine differences in the correlation values. Differences in sexes were evaluated using two-way analysis of variance. A multivariate backward linear regression model was used to determine whether a combination of variables (sex, ATMA, MT length, Hallux length, Arch Stiffness) were able to predict the jump heights of the different jumps. The level of significance was set at $\alpha = 0.01$ for all tests.

Results showed positive relationships were found among hallux length with ASJ, ACMJ, SJ, and CMJ peak ankle power ($p<0.001$), ATMA positively correlated with ASJ, ACMJ, SJ, and CMJ peak ankle power ($p<0.001$), MT length correlated with ACMJ ankle peak power ($p<0.001$), hallux length and ATMA positively correlated with SJ peak negative MTP power ($p<0.001$), ATMA correlated with SJ jump height and CMJ jump height ($p<0.001$). Fisher's exact tests revealed no significant differences in correlation strength between the different anthropometric measures and different types of jumps ($0.08<p<0.96$). Results from the two-way ANOVA and multivariate backward linear regression model found that males and females had significantly different performance results and that sex was the only significant predictor for jump height. Although correlational relationships were found, after results were controlled for sex these relationships disappeared. This indicates that sex differences are critical when evaluating foot anthropometric relationships with jump performance. Previous correlations that have been found may be due to sex, activity level, or small sample sizes. Future research should consider much larger sample sizes and controlling for possible confounding factors.

Acknowledgments

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Chapter 1: Introduction

The foot is critical during general movement as it directly interacts with the ground and is therefore subject to the associated ground contact forces. Research has shown that foot structure has evolved across species of animals gaining selective advantages in movement (Hildebrand, 1960). It is suggested that foot structure in humans have adapted and evolved over the generations for bipedal walking and running (Wang & Crompton, 2004). Across animal species foot structure has been shown to differ depending on their specialization of task (Hildebrand, 1960). For example, foot structure and ankle position of badger, deer, and cheetahs all differ according to their specialization (Hildebrand, 1960). Badgers have shorter metatarsals and ankle position that make them more advantageous for power production in digging (Hildebrand, 1960). However, deer and cheetahs have longer metatarsals and ankle position that are specific to efficient running and speed (Hildebrand, 1960).

Although between-species differences are evident, there is also the potential that within-species differences, specifically as it relates to humans, can influence performance in various activities. Various researchers have tried to link performance in powerful movements such as sprinting and jumping to foot structure. Two particular anthropometric foot measures have received considerable attention: toe length (e.g., Baxter, Novack, Van Werkhoven, Pennell, & Piazza, 2011; Lee & Piazza, 2009; Rolain et al., 2009); and Achilles tendon moment arm (ATMA) or associated heel length (e.g., Baxter & Piazza, 2014; Raichlin, Armstrong, & Lieberman, 2011; van Werkhoven & Piazza, 2017b). Research focusing on sprinting have consistently shown that sprinters have longer toes and shorter ATMAs compared to non-sprinters (Baxter et al., 2011; Lee & Piazza, 2009). In trying to understand the potential mechanism by which foot anthropometry affects performance, investigators have employed a few different frameworks. For example, Lee and Piazza (2009) and Baxter et al. (2011) have used computational models of the ankle or ankle and MTP joint to explore reasons for relationships between performance and anthropometry. It has been shown that longer toes potentially allow for longer foot contact time, which increases impulse produced during push-off (Lee & Piazza, 2009). It has also been suggested that shorter ATMA allows for plantar flexor muscles to operate at a more favorable position on the force-velocity curve (Baxter & Piazza, 2014). Similarly, Nagano and Komura (2003) have shown that smaller ankle moment arms increase joint torque and joint power at speeds associated with fast movement. Combined, these results seem to indicate that for powerful movements, such as sprinting, longer toes and shorter heels seem to be beneficial.

However, not all findings support the above mechanism for performance improvement in powerful movements. Using an isokinetic dynamometer, Baxter et al. (2014) found that joint torque is positively correlated with ATMA across a large range of ankle rotation speeds, indicating that longer, not shorter, ATMAs are critical in providing torque during movement, even at faster speeds. Results from Baxter et al. (2014) were confirmed by others using a simplified jumping protocol, where subject knees and hips were fixed and only the foot and ankle were used for jumping (van Werkhoven & Piazza, 2017b). These investigators found that subjects with longer heels, a proxy measure for ATMA, were indeed able to jump higher (van Werkhoven & Piazza, 2017b). Regarding toe length, van Werkhoven and Piazza (2017b) found that longer toes also related to higher jumps. More recently, Hawley (2016) found a negative correlation between toe length and jump height for women, but no correlation between jump height and heel length for either men or women. This group used a full body lower extremity jump protocol (Hawley, 2016).

It is unclear why results from Baxter and Piazza (2014) using an isokinetic dynamometer at the ankle joint and van Werkhoven and Piazza (2017b), with foot jumping, identify longer heels as better, whereas full body tasks such as sprinting (Lee & Piazza, 2009; Baxter et al., 2011) and computational models (Nagano & Komura, 2003) show shorter heels to be better. There are several differences in the study designs that do make direct comparison problematic. One such difference is associated with the experimental design used, specifically related to the complexity of the movements. In some cases, whole body movements, such as sprinting or full lower extremity jumping, are compared against single joint (ankle only) or foot movements. It is not necessarily clear why differences in movement complexity will create different relationships between foot anthropometry and performance, however, this could potentially give rise to confounding results.

Apart from toe length and ATMA length (and associated heel length), arch height measures are also of interest. Medial longitudinal arch height and stiffness have not been extensively studied as to its effects on movements such as jumping, with only two studies (Hawley, 2016; Zhao Tsujimoto, Kim, & Tanaka, 2017) relating arch height to jump performance. Both of these studies showed no relationship. However, since it is has been shown that the medial longitudinal arch has the ability to store elastic energy during running and that high arched individuals are able to better transfer force in the foot, it is feasible that arch stiffness might affect performance in tasks such as jumping as well (Stearne et al., 2016; Powell, Williams 3rd, Windsor, Butler, & Zhang, 2014). This potential link warrants further investigation.

Creating an experimental framework in which the relationship among foot anthropometry and performance is investigated using tasks of varying movement complexity within a single subject group might help us to better understand these relationships and mechanics associated with the relationships. Therefore, the aim of this study was to investigate whether movement complexity influences the relationships among common foot anthropometric measures and jump performance.

Specific Aim 1

Determine the relationship between toe length and jump performance measures during simulated vertical jumps of different complexities (foot and ankle only vs whole lower extremity)

Hypothesis 1

There would be a positive correlation between hallux length and ankle peak joint power and hallux length and jump height regardless of movement complexity

Specific Aim 2

Determine the relationship between ATMA and jump performance measures during a simulated vertical jumps of different complexities (foot and ankle only versus whole lower extremity)

Hypothesis 2

There would be a positive correlation between ATMA length and ankle peak joint power and ATMA length and jump height regardless of movement complexity

Specific Aim 3

Determine the relationship between medial longitudinal arch stiffness and jump performance measures during a simulated vertical jumps of different complexities (foot only versus whole lower extremity)

Hypothesis 3

There would be a positive correlation between medial longitudinal arch stiffness and ankle joint power regardless of movement complexity

Chapter 2: Review of Literature

Toes and Performance

The foot has five toes that are comprised of phalanges. The hallux, first toe, is comprised of a proximal and a distal phalange. The other four toes are comprised of proximal, middle, and distal phalanges (Netter & Colcacino, 1989) (Figure 1). When considering the association between toe length and performance in various tasks, toe bone length has been commonly measured using magnetic resonance imaging and external measures from photography (Baxter et al., 2011; Lee & Piazza, 2009; Tanaka, Suga, Otsuka, Misaki, Miyake, Kudo, & Isaka, 2017; van Werkhoven & Piazza, 2017b). Researchers have used different measures to define "toe" length such as phalanges only (Baxter et al., 2011; Lee & Piazza, 2009; Tanaka et al., 2017; van Werkhoven & Piazza, 2017b) and phalanges plus metatarsals (Tanaka et al., 2017). Several studies have investigated the relationship between

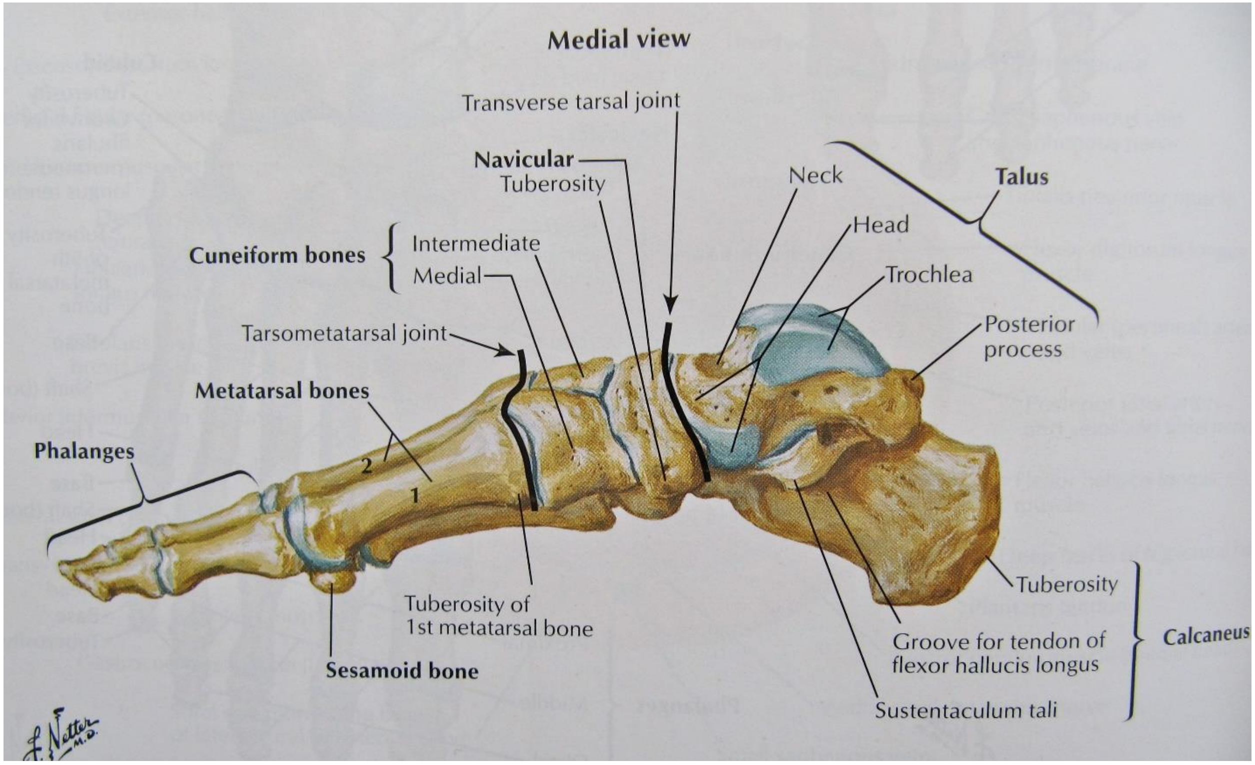

Figure 1. Foot bone structure (Netter & Colacino, 1989)

hallux length and task specific performance (Baxter et al., 2011; Rolian, Lieberman, Hamill, Scott, & Werbel, 2009; van Werkhoven & Piazza, 2017b). Hallux length has the potential to influence the gear ratio of the foot (Carrier, Heglund, & Earls, 1994). Foot gear ratio can be defined as the ratio of the perpendicular distance from the ankle joint center to the plantar flexor muscle line of force to the perpendicular distance from the ankle joint center to the line of action of the ground reaction force (Carrier et al., 1994). For example, as the foot strikes and rolls through push-off during running, the ground reaction force moment arm changes length, and this length change is dependent on the length of the forefoot, and ultimately the toe length. Carrier et al. (1994) investigated how a longer ground reaction force moment arm, which increases the gear ratio, allows the plantar flexor muscles to operate at a lower velocity, and therefore higher force producing ability at constant velocity during running (Carrier et al., 1994). Several investigators have looked at the differences in toe length between sprinters and non-sprinters (Lee & Piazza, 2009; Baxter et al., 2011; Tanaka et al., 2017) and have found that sprinters have longer toes than the non-sprinters. To explain these results Baxter et al. (2011) and Lee and Piazza (2009) used a simplified foot model to show that longer toes potentially allow for a longer contact time with the ground during push-off. The longer contact time with the ground, the greater impulse of force production can occur.

Hallux length has also been of interest in running metabolic efficiency. Rolain et al. (2009) investigated the effect of hallux length on running economy and found it to increase the amount of negative work done at the MTP joint during running. Similar to Baxter et al. (2011), a computational model, this time of the metatarsals and phalanges only, showed that longer toes increased negative work. This was experimentally validated, with runners with longer toes showing larger negative impulse and joint work at the MTP joint. The authors argued, although did not experimentally test this, that this will lead to higher metabolic cost and that shorter toes are linked to more efficient running. More recently, van Werkhoven and Piazza (2017a) directly investigated the link between toe length and running economy but did not find any significant relationship.

Hallux length has also been investigated for its influence in jumping performance. Van Werkhoven and Piazza (2017b) investigated the relationship between foot anthropometry and performance in a modified jump task, where movement at the hip and knee was constrained. They found a positive relationship between hallux length and maximal jump height during this so-called single-joint jumping task at the ankle and foot. The ankle has been shown to contribute 23 percent of the work performed during a full lower extremity jump (Hubley & Wells, 1983). The relationship may be affected by including more joints in the total work being performed.

From the studies discussed, it is evident that toe length has the potential to influence lower extremity propulsion in various tasks. However, the type of task, as well as how the analysis was done, i.e., multi- vs single-joint, experimental vs computational models should be considered as reasons for lack of consistency between the results from different studies.

Metatarsal Phalangeal Joint

The foot has five metatarsals that join the tarsals to the phalanges at the metatarsal phalangeal (MTP) joint (Netter & Colacino, 1989) (Figure 1). The foot has been researched as a single segment, as well as a multi-segmental body. Although the ankle has been the main joint of interest in research, some have investigated the MTP joint and its role in propulsion. Mager et al. (2018) investigated the MTP joint stiffness and its influence in running joint stiffness is the quantification of the joints ability to attenuate load impact (Mager et al., 2018). Joint stiffness can also be interpreted as the muscular and tendinous structures ability to store elastic energy (Mager et al., 2018). Mager et al (2018) reported that while running, both the ankle and MTP joint demonstrated levels of joint stiffness that were advantageous for propulsion. During the running task, joint moments increased with increased joint stiffness. MTP joint stiffness influences propulsion in running through increasing its ability to transfer force and contact time resulting in greater work done at the joint (Honert, Bastas, & Zelik, 2018; Willwacher, Konig, Braunstien, Goldmann, & Bruggemann, 2014). Literature has also looked at the MTP joint and its roles in performance in running. Krell and Stefanyshyn in 2006 investigated 100-meter sprint times for both men and women. They found that faster times were correlated to increased rates of MTP extension during running. However, research has also shown that at running speeds, the MTP performs as an energy absorber resulting in negative work (Stefanyshyn & Nigg, 1997). Research has shown that MTP plays a pivotal role in propulsion and adds to the lower extremity kinetic chain. Investigations into predictors of jump height found peak power is a positive predictor for jump height (Árágón-Vargas & Gross, 1997; Dowling & Vamos, 1993). Foot anthropometry may have a relationship with MTP power production since it has a role in lower extremity propulsion.

Medial Longitudinal Arch Height and Performance

The arch of the foot helps with distributing weight and shock absorbing. The tarsals and metatarsals of the foot create an arch in the foot (Moore, Agur, & Dalley, 2015). The bones of the foot are connected by ligaments that allow for the foot to flex and absorb shock (Moore et al., 2015). Medial longitudinal arch height is a characteristic of the foot that is commonly measured using calipers, radiographs, footprints, and photographs (Williams &

McClay, 2000). Methods for determining medial longitudinal arch height are navicular height; height of the dorsum of the foot at 50% of foot length; angle of the first metatarsal; navicular height divided by foot length; navicular height divided by truncated foot length, dorsum height divided by foot length, and dorsum height divided by truncated foot length (Williams & McClay, 2000).

Medial longitudinal arch height has been an area of focus for studies that involve running and injury patterns (Nakhaee, Rahimi, Abaee, Rezasoltani, & Kalantari, 2008; Williams, McClay, & Hamill, 2001). Differences in structure of the arch of the foot has been shown to influence injury patterns (Nakhaee et al., 2008; Williams et al., 2001). Even though the arch of the foot is a complex articulating structure, it is often modeled as a rigid segment. Two common measures of interest associated with the medial longitudinal arch are arch stiffness and arch height. Medial longitudinal arch stiffness is a measure of arch deformation and ability to attenuate loads (Zhoa et al., 2017; Zifchock, Davis, Hillstrom, & Song, 2006). Medial longitudinal arch stiffness can be defined as the difference in medial longitudinal arch height index from 10% weight bearing to 90% weight bearing (Zifchock et al., 2006). Previous research has investigated potential links between medial longitudinal arch height index, medial longitudinal arch stiffness, and ankle strength (Zhoa et al., 2017). Zhoa et al. (2017) found that low arch height individuals exhibited less medial longitudinal arch stiffness and greater ankle strength. They failed to find a relationship between medial longitudinal arch height and jump height performance (Zhoa et al., 2017). However medial longitudinal stiffness has been shown to have a relationship with knee excursion during landing (Howard, Fazio, Mattacola, Uhl, & Jacobs, 2011), suggesting that arch stiffness influences movement up the chain of the lower extremity. In general, medial longitudinal arch height has not been extensively researched regarding foot anthropometry and its relationship with performance. However, a study investigating the dynamic joint stiffness in a running task found that high arch athletes produced smaller amounts of ankle work in propulsion (Powell et al., 2014). Dynamic joint stiffness is a measurement that evaluates the joint ability to attenuate forces on impact and the ability to store energy (Powell et al., 2014). This relationship was found by utilizing a dynamometer which decreased the complexity of the movement. Zifchock et al. (2006) also found a relationship between higher arches having a higher arch stiffness score. This arch stiffness was found by measuring arch deformation during weight bearing standing (Zifchock et al., 2006). Individuals with high arches produce higher arch stiffness adding the advantage of the foot being a better lever to transfer force (Powell et al., 2014). The opposite is for low arch individuals lose the efficiency in transferring force for propulsion (Powell et al., 2014).

Research has also eluded to the statement that arch height doesn’t have an influence in performance of lower extremity tasks but can determine adaptations of strength for attenuation of impact forces (Zhoa et al., 2017). The past research in arch height have found varying relationships in arch height and its influence on ankle strength and arch stiffness. These relationships have been found in varying movements such as jumping, plantarflexion, and standing. The movements complexity could be the reason why there are differences in the relationships since it has been shown to influence joint contributions up the chain (Howard et al., 2011).

Achilles Tendon Moment Arm and Performance

The ankle joint that connects the rear foot to the tibia and fibula. The rear foot encompasses the talus and the calcaneus (Netter & Colacino, 1989) (Figure 1). The ankle can be broken down to two oblique joints, the talocrural joint and the subtalar joint (Moore et al., 2015). The main joint associated with plantarflexion and dorsiflexion is the talocrural joint. The main plantar flexor muscles responsible for motion attach on the tuberosity of the calcaneus (Moore et al., 2015) (Figure 1). Joint moments of force are produced when a force is applied on a rigid body at a distance from the axis of rotation. Moments of force is a product of the moment arm and the force applied. For the ankle, the Achilles tendon moment arm length represents the plantar flexor muscles' potential to produce turning force at the joint.

The gold standard for measuring Achilles tendon moment arm has been the center of rotation method utilizing MRI (Fath, Blazevich, Waugh, Miller, & Korff, 2010). In the center of rotation method MRI images are taken of the ankle at different joint angles to determine the ankle center of rotation (Fath et al., 2010). Another internal measure that is used to measure Achilles tendon moment arm is the tendon excursion method (Fath et al., 2010). The tendon excursion method utilizes ultrasonography to measure Achilles tendon angle changes throughout the ankle range of motion (Fath et al., 2010). The angle changes of the tendon are then divided by ankle angle to determine moment arm length of the Achilles tendon (Fath et al., 2010). X-ray imaging has also been used to estimate moment arm length by utilizing a circle that is fitted over the concave portion of the talus to determine center of rotation (Figure 2) (Barnett & Napier, 1952).

Heel length has been used as an external measure to represent the Achilles tendon moment arm length. Heel length has been associated with the moment arm length of the Achilles tendon due to its length being representative of an estimation of the distance from the center of rotation and point of force application. External measures of the heel are commonly used to estimate the moment arm length due to limitations in access and cost of these internal measures (Scholz, Bobbert, Van Soest, Clark, & van Heerden, 2008; van Werkhoven & Piazza, 2017b). In external measures of the heel length digital photography is often used to measure from the malleoli to the Achilles tendon (Scholz et al., 2008; van Werkhoven & Piazza, 2017b).

The relationship between ATMA length or associated heel length and performance has been the focus of many previous studies. Sprinters have been found to have shorter ATMA lengths compared to untrained individuals (Baxter et al., 2011; Lee & Piazza, 2009). The authors have argued that a smaller plantar flexor moment arm allows for muscles to perform at a more favorable position on the force-velocity curve. Baxter and Lee used computational

Figure 2. Radiography Image of ATMA measurement

models of the foot to show how a smaller moment arm, like those found in the sprinters, improve force producing capabilities of the muscle.

ATMA length has also been shown to influence running metabolic efficiency. Past research has shown that shorter ATMA, or more specifically heel lengths, correlate with better metabolic efficiency in endurance running (Barnes, McGuigan, & Kilding, 2014; Raichlen, Armstrong, & Lieberman, 2011; Scholz et al., 2008). It is argued that smaller moment arms allow for larger muscle force, which in turn is associated with increased energy storage in the Achilles tendon (Scholz et al., 2008). However, others have not found these relationships. Both van Werkhoven and Piazza (2017a) and Gruber (2012) investigated metabolic cost of runners and found no relationship between heel length and metabolic cost of running. This conflicting information warrants further investigation.

Jumping is a complex movement that is dynamic and includes multi-joint coordination. ATMA length has the potential to also influence jump performance. Watanabe, Koyama, and Yanagiya (2008) investigated Achilles tendon moment arm and jump performance in volleyball players, distance runners, and untrained individuals (Watanabe et al., 2008). Volleyball players compared to the untrained individuals had shorter ATMAs and jumped higher (Watanabe et al., 2008). Watanabe et al. (2008) also found that the volleyball players jumped higher than the distance runners despite no difference in ATMA length. In untrained individuals, van Werkhoven and Piazza (2017b) also investigated heel length and its relationship with jump height. Untrained individuals with longer heels jumped higher (van Werkhoven & Piazza, 2017b). Both studies by Wanatabe et al. (2008) and van Werkhoven and Piazza (2017b) had subjects perform ankle jumps, not whole body jumps, to investigate the relationship of ATMA length and jump height. Peak ankle joint power has been shown to be a predictor for jump height in a single leg jump (Johnston, Butler, Sparling, & Queen, 2015). If both ATMA and peak ankle joint powers can predict jump height, then ATMA may have to potential to predict joint powers.

The influence of ATMA length on lower extremity performance has also been investigated using less ecologically valid frameworks. These include the use of isokinetic dynamometers or computer models. Baxter and Piazza (2014) utilized an isokinetic dynamometer strength test at varying speeds to show that longer ATMAs resulted in higher torque production across all speeds (Baxter & Piazza, 2014). Using a dynamometer decreases the complexity of the movement compared to a highly complex movement like sprinting. ATMA length has also been investigated by employing various computer models. In a Hill type model of the ankle and soleus muscle, larger Achilles moment arms resulted in larger shortening velocity due to the force-velocity relationship of muscles (Nagano & Komura, 2003). The results of the model also showed that the larger moment arm length created smaller joint moments thus creating small amounts of joint power and work (Nagano & Komura, 2003). The model of the lower leg was a single joint analysis of the ankle, again resulting in a simple movement. These relationships and analysis maybe affected by different joint contributions during the movement. Increasing joint a single joint contribution in the movement has the potential to influence the relationship between ATMA and jump performance.

In summary ATMA length has a complex influence on force and power production of the foot. Even though sprinting and jumping could be considered as similar tasks, results from experiential studies, as well as studies employing other techniques, show that findings often vary. Sprinters have shorter moment arms that non-sprinters, whereas a positive relationship exists between jump height and heel length. Even when employing more basic methods such as isokinetic dynamometers or computational models, answers are not always clear. Differences in results could obviously be due to different tasks being performed. However, some differences could also be explained due to the different models used, whether it is using models with different complexity, as in more or less joints used, or using different modalities, actual jump vs isokinetic dynamometer vs computation models.

Conclusion

In summary toe length, arch stiffness, and Achilles tendon moment arm have been investigated in human movements using various protocols. These protocols consisted of multi- versus single joint and experimental versus modeling methods. Although some results regarding these relationships seems consistent, this is not always the case. Differences could be due to different movements or sports performed but may be due to different protocols or frameworks being used.

Chapter 3: Methods

Participants

Forty subjects, 20 males and 20 females, (age: 22 ± 2.5 y; height: 172.3 ± 10.3 cm; body mass: 75.3 ± 15.1 kg) were recruited to participate in this study. Participants were healthy with no history of lower extremity injury in the past six months, no lower extremity fracture; not currently pregnant; and did not have a pacemaker/automated defibrillator. Participants filled out a health screening questionnaire to determine if they were healthy and at low risk to participate in exercise.

Testing procedure

Participants came to the biomechanics lab for an estimated one-hour time slot for testing. Upon arrival participants were asked for written oral informed consent. Participants weight and height were recorded along with photographs taken of the right foot. Dual energy x-ray absorptiometry (DEXA) scans of the participants foot and ankle were taken. This was followed by plantar flexor strength testing on a custom sled (Figure 3). Finally, subjects performed four different single leg jumps on the custom sled while force and marker data were collected.

Anthropometric measures

Height and weight were measured utilizing a stadiometer and weight scale. External measures of subjects' feet were performed using photography of the lower leg to measure the medial longitudinal arch height and stiffness in congruence with past studies (Chang, Hung,

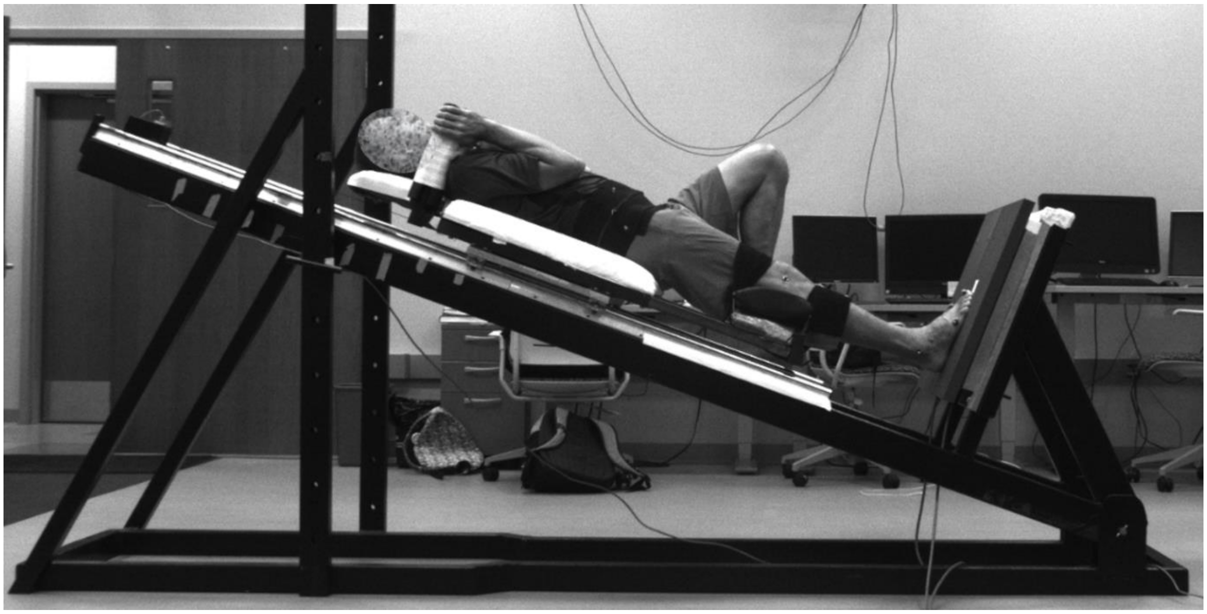

Figure 3. Custom sled with participant in position to perform jump

Wu, Chiu, & Hsu, 2010; Williams et al., 2001; Zifchock et al., 2006; Howard et al., 2011). Two images of the right leg and foot were taken at 10 percent weight bearing and 90 percent weight bearing (Williams et al., 2001). Medial longitudinal arch height measurement was the height of the navicular tuberosity divided by the truncated foot length (Williams & McClay, 2000). Medial longitudinal arch stiffness was calculated by the following equation, modified from Howard and colleagues (Howard et al., 2011):

$$\text{Arch Stiffness} = (AH_{10\%\ BW} - AH_{90\%\ BW}) / AH_{10\%\ BW}$$

Subjects were instructed to place their right foot on a reference block/weight scale, aligning their foot with the lateral edge of the block, and position their knee above the ankle. Marks were placed on the subject's navicular tuberosity before two photos were taken. All images were processed using a custom MATLAB code (The Mathworks, Inc., Natick, MA).

DEXA:

Two scans of the subject's right foot and ankle were taken using DEXA, SE femur scan (Hologic inc, USA), similar to the method of Erskine, Morse, Day, Williams, and Onambele-

Pearson (2014). For the medial scan subjects were seated next to the scanner with their foot rotated so that their toes point up towards the head of the scanner and placed medial side up. Subjects were told to keep their foot at a 90 degree angle at the ankle and at the knee measured by goniometer. The subjects were told to keep their foot at a neutral 0 degree plantar flexion. For the dorsal scan subjects were seated at the head of the scanner with their foot flat and toes pointed towards the bottom of the scanner. Scans were utilized to measure hallux length, metatarsal length and ATMA length. Hallux length was measured as defined by Baxter et al. (2011). Hallux length was measured in the dorsal scan as the sum of the length of the distal and proximal phalanges of the hallux (Figure 4). ATMA length was measured in the medial scan as the shortest distance from the center of rotation of the ankle to the most posterior aspect of the Achilles tendon (Figure 4) (Baxter et al., 2011). Ankle joint center of rotation was determined by fitting a circle to the concave portion of the distal tibia and finding the center of the circle marking the joint center (Figure 4) (Barnett & Napier, 1952). Both of these scans were 15 seconds in duration.

Jump Performance:

The participants were barefoot and instrumented with eight reflective markers on the anterior superior iliac spine, greater trochanter, lateral epicondyle of the knee, lateral malleolus, dorsum at 50 percent of the foot, top of first MTP, lateral of the fifth MTP, and hallux nail bed. Instrumentation was on their right leg only. They were then asked to get on the instrumented sled that had two Bertec force plates (Model FP4060-07) set at an inclination of 20 degrees. One high speed camera and Max TRAQ 2-D software (Innovision

System Inc., Marietta, GA, USA) were utilized to collect data. Participants performed two single leg countermovement jumps and two single leg squat jumps with just the ankle and one minute rest in between jumps. Then two single leg countermovement jumps and two single leg squat jumps utilizing all lower extremity joints with one-minute rest in between jumps. Squat jumps for the ankle were defined as a jump with only upward propulsion with

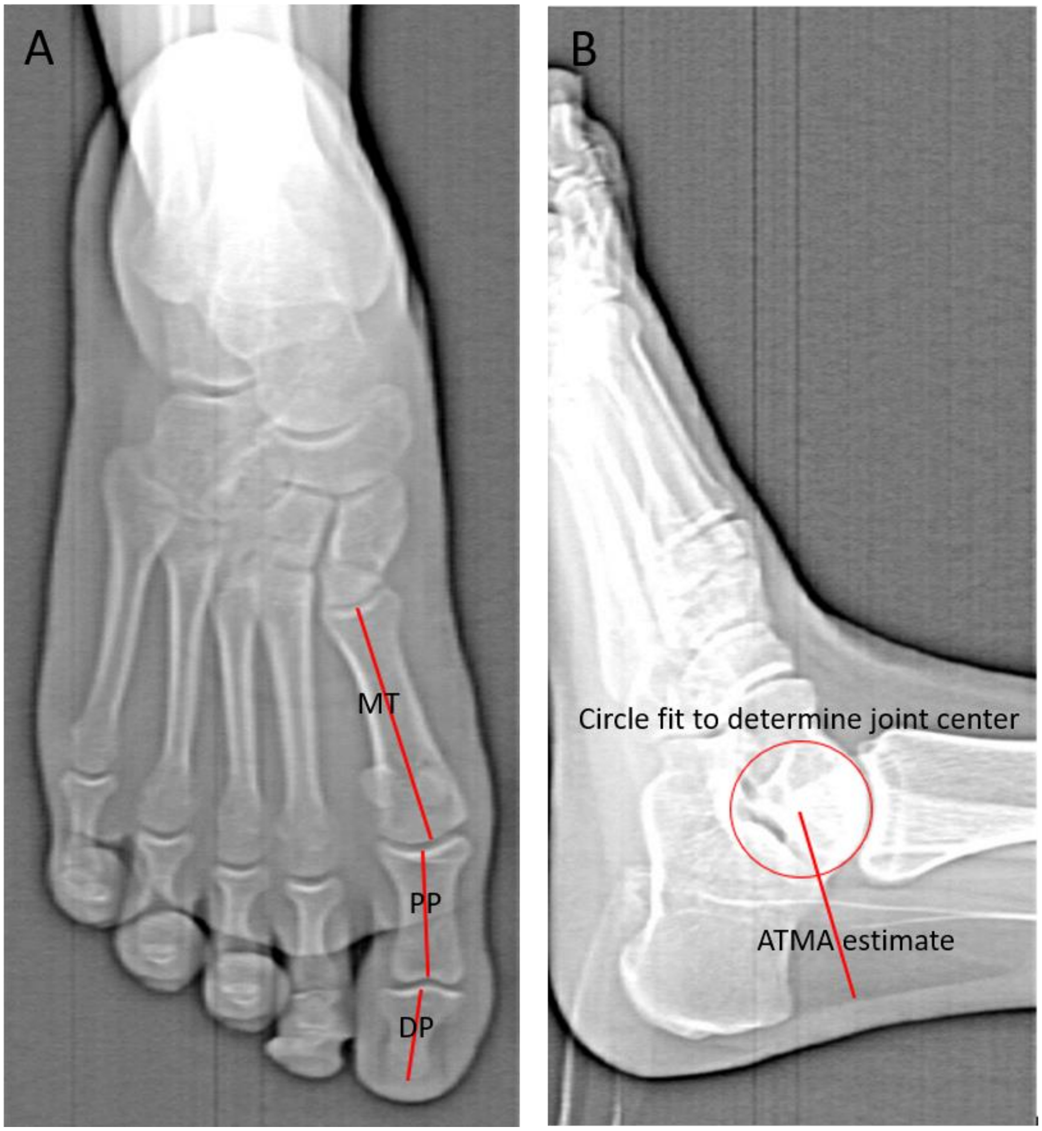

Figure 4. A. DEXA image showing hallux measurements: metatarsal (MT), proximal phalange (PP) and distal phalange (DP). **B.** DEXA Image showing circle fit to distal end of the tibia and the moment arm generated from center of circle fit to estimated position of the Achilles tendon at the back of the heel.

the whole foot in contact with the force plate prior to movement. Counter movement jumps for the ankle were defined as a jump with a starting position in a plantar flexed at the ankle, then dorsiflexion into plantarflexion propulsion. Jump order was randomized by involved joints (ankle only or all lower extremity) and performed with the right leg. Jump height was recorded using a linear transducer placed at the top of the modified sled measuring displacement of the sled. Kinematic data were collected at 100 Hz. Force plate data were collected at 1000 Hz. Marker position data as well as force plate data were low-pass filtered at 10 Hz. Inverse dynamics calculations were performed using marker and force plate data to calculate jump performance as joint kinetics, including peak joint power during the tasks for the MTP joint and ankle.

Statistics

Using SPSS, Pearson product-moment correlation coefficients were calculated to determine relationships among foot anthropometric measurements (ATMA, MT length, hallux length, and arch stiffness), jump height, and peak joint power at the MTP and ankle for all jump complexities. Data were also analyzed using three 2x4 ANOVA’s (within-subjects factor of condition, 4 levels; between-subjects factor of sex, 2 levels). The dependent variables for each ANOVA were jump height, peak ankle power, and peak negative MTP power. A Fisher exact test was performed to determine differences in the correlation coefficients between the two jump types. A multivariate backward linear regression model was used to determine whether a combination of variables (sex, ATMA, MT length, Hallux length, Arch stiffness) were able to predict the jump heights of the different jumps. The level of significance was set at $\alpha = 0.01$ for all tests.

Chapter 4: Results

Descriptive values for anthropometric measurements of subjects and jump heights for each condition are presented in Table 1.

Table 1. Descriptive values for anthropometric measurements of subjects and jump heights for each condition.

	Males	Females	All Subjects
ATMA (mm)	49.9 ± 3.8	44.5 ± 3.1	47.2 ± 4.4
MT Length (mm)	57.3 ± 4.4	54.3 ± 3.1	55.8 ± 4.1
Hallux Length (mm)	54.4 ± 3.7	49.8 ± 3.7	52.1 ± 4.4
Arch Stiffness	6.4 ± 6.2	8.2 ± 4.7	7.3 ± 5.5
ASJ Jump Height (cm)	16.3 ± 3.4	13.4 ± 2.5	14.8 ± 3.3
ACMJ Jump Height (cm)	18.1 ± 3.3	13.0 ± 1.8	15.5 ± 3.7
SJ Jump Height (cm)	43.9 ± 10.9	28.6 ± 6.3	36.2 ± 11.7
CMJ Jump Height (cm)	46.3 14.3	31.0 7.0	38.7 ± 13.5

Correlations between anthropometric variables and performance variables for all participants are presented in Table 2. Hallux length correlated with peak ankle power during ASJ (r=0.428, p=0.006), ACMJ (r=0.532, p<0.001), SJ (r=0.530, p<0.001), and CMJ (r=0.432, p=0.005), whereby greater peak ankle power during ASJ, ACMJ, SJ, and CMJ was associated with longer hallux. ATMA correlated with ASJ(r=0.408, p=0.009), ACMJ(r=0.504, p=0.001), SJ(r=0.568, p<0.001), and CMJ (r=0.435, p=0.005) peak ankle power whereby greater peak ankle power during ASJ, ACMJ, SJ, and CMJ was associated

Table 2. Pearson product-moment correlation coefficients between anthropometric measures and performance measures for all participants. * - significant correlation (p<0.01)

		ATMA	MT Length	Hallux Length	Arch Stiffness
Ankle SJ	Jump height	0.159(p=0.326)	0.123(p=0.449)	0.138(p=0.395)	-0.188(p=0.245)
	MTP power	0.278(p=0.082)	0.184(p=0.256)	0.299(p=0.061)	-0.193(p=0.233)
	Ankle power	0.408(p=0.009)*	0.295(p=0.065)	0.428(p=0.006)*	-0.377(p=0.017)
Ankle CMJ	Jump height	0.393(p=0.012)	0.202(p=0.211)	0.293(p=0.066)	-0.107(p=0.511)
	MTP power	0.372(p=0.018)	0.387(p=0.014)	0.426(p=0.006)*	-0.080(p=0.624)
	Ankle power	0.504(p=0.001)*	0.426(p=0.006)*	0.532(p<0.001)*	-0.261(p=0.104)
SJ	Jump height	0.486(p=0.001)*	0.289(p=0.071)	0.357(p=0.024)	0.072(p=0.660)
	MTP power	0.418(p=0.007)*	0.286(p=0.073)	0.416(p=0.008)*	0.069(p=0.672)
	Ankle power	0.568(p<0.001)*	0.376(p=0.017)	0.530(p<0.001)*	0.015(p=0.929)
CMJ	Jump height	0.407(p=0.009)*	0.191(p=0.237)	0.314(p=0.048)	0.005(p=0.975)
	MTP power	0.283(p=0.077)	0.199(p=0.219)	0.353(p=0.025)	-0.032(p=0.844)
	Ankle power	0.435(p=0.005)*	0.277(p=0.084)	0.432(p=0.005)*	0.010(p=0.949)

with longer ATMA. Also, MT length correlated with ACMJ ankle peak power (r=0.426, p=0.006), whereby greater ACMJ ankle peak power was associated with longer MT. Hallux length and ATMA positively correlated with SJ peak negative MTP power (r=0.416, p=0.008; r=0.418, p=0.007), thus an increase in SJ peak negative MTP power was associated with longer hallux and ATMA. ATMA significantly correlated with SJ jump height (r=0.486, p=0.001) and CMJ jump height (r=0.407, p=0.009), whereby greater jump heights in the SJ and CMJ was associated with longer ATMA (Figure 5).

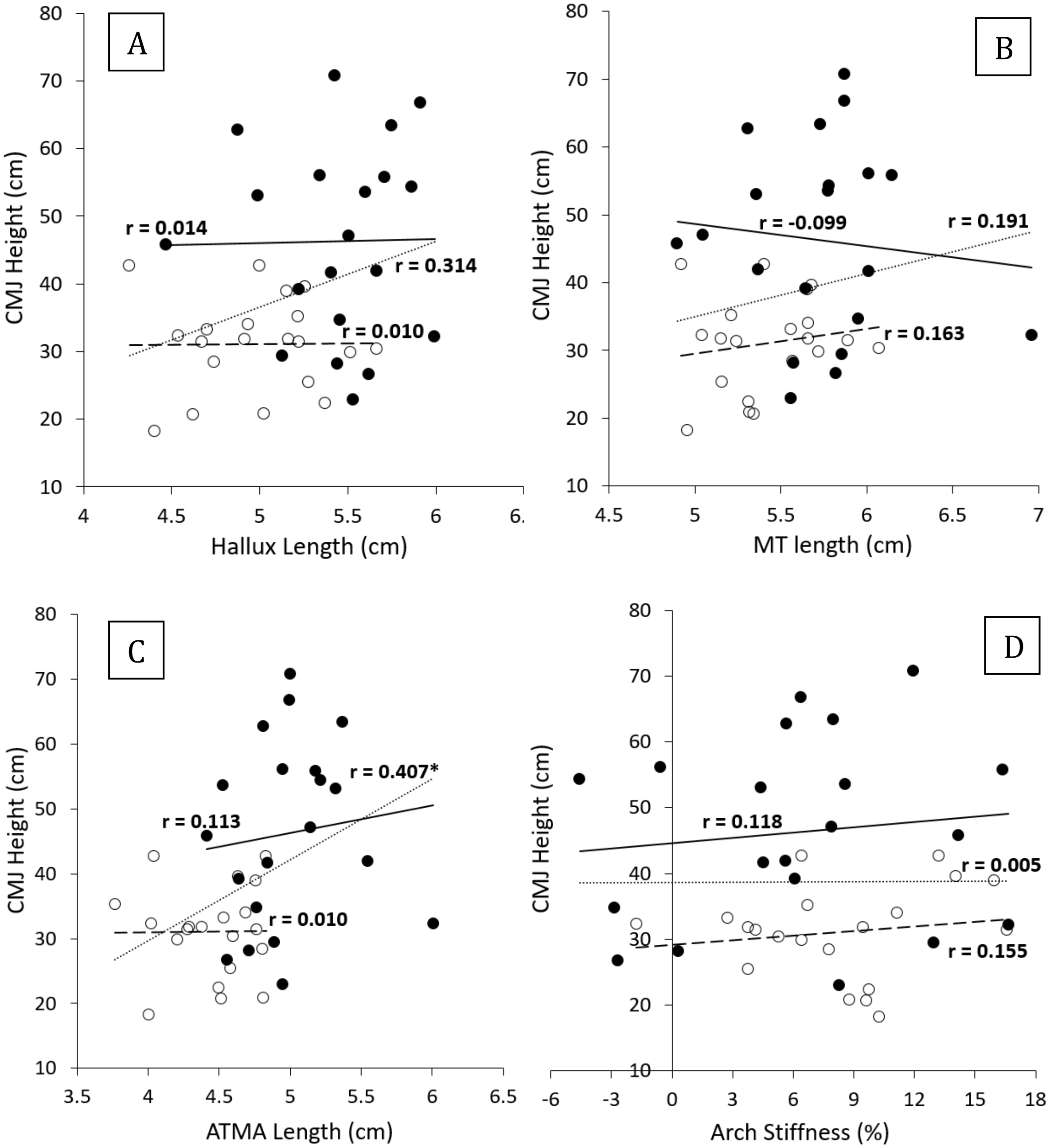

Figure 5. CMJ jump height plotted against each anthropometric measurement (A: Hallux Length, B: MT Length, C: ATMA Length, D: Arch Stiffness). Each sex is represented in each plot (Males: ●, Females: ○). Correlations are represented for ALL (•••), Males (—), and Females (---). * - significant correlation (p<0.01)

No significant correlations were found between anthropometric measures and performance measures for either males or females when separate by gender (Table 3, Table 4). Fisher exact test results showed no significant differences in relationships between anthropometric variables and jump performance variables from ankle only jumps to full lower extremity jumps for all subjects (Table 5).

Factorial analyses of variance revealed for jump height there was a significant Condition-by-Sex interaction effect ($F[3,114]=12.715$, $p<0.001$, $\eta^2=0.251$). Fisher's LSD pairwise comparisons revealed that sexes were different from each other across all conditions ($p\leq0.005$). For females, ankle jump heights were significantly different from full lower extremity jumps heights ($p<0.001$), but there were no differences between ACMJ and ASJ ($p=0.336$) or SJ & CMJ ($p=0.137$). For males, no differences were observed between SJ and CMJ ($p=0.134$), but all other jump conditions were significantly different from each other ($p<0.001$). For ankle power there was a significant Condition-by-Sex interaction effect ($F[3,114]=8.731$, $p<0.001$, $\eta^2=0.187$). Fisher's LSD pairwise comparisons revealed that sexes were different from each other across all conditions ($p\leq0.005$). For female's ankle power, ankle jumps were significantly different from full lower extremity jumps ($p<0.001$), but there were no differences between ACMJ and ASJ ($p=0.772$) or SJ & CMJ ($p=0.930$). For males, ankle power was significantly different across all conditions. Full lower extremity jumps had significantly more power than ankle jumps ($p<0.001$), while ACMJ had greater ankle power than ASJ ($p=0.014$), and CMJ had greater ankle power than SJ ($p=0.028$). For peak negative MTP power there was no significant condition-by-sex interaction effect ($F[3,114]=0.691$, $p=0.559$, $\eta^2=0.018$). Results showed there was a significant main effect of condition for peak negative MTP power ($F[3,114]=4.352$, $p=0.006$, $\eta^2=0.103$). Also, there was a significant main effect of sex for peak negative MTP power (F[1,38]=7.702, p=0.009, η^2=0.169).

Table 3. Pearson product-moment correlation coefficients between anthropometric measures and performance measures for females only. * - significant correlation (p<0.01)

		ATMA	MT Length	Hallux Length	Arch Stiffness
Ankle SJ	Jump height	-0.237(p=0.315)	-0.062(p=0.796)	-0.227(p=0.335)	-0.169(p=0.477)
	MTP power	-0.185(p=0.435)	0.110(p=0.644)	0.052(p=0.828)	-0.335(p=0.148)
	Ankle power	-0.201(p=0.395)	0.047(p=0.843)	-0.138(p=0.562)	-0.545(p=0.013)
Ankle CMJ	Jump height	-0.157(p=0.508)	0.161(p=0.498)	-0.057(p=0.812)	-0.181(p=0.446)
	MTP power	-0.296(p=0.205)	0.283(p=0.227)	0.050(p=0.836)	-0.235(p=0.319)
	Ankle power	-0.117(p=0.624)	0.399(p=0.081)	0.035(p=0.883)	-0.349(p=0.131)
SJ	Jump height	0.093(p=0.696)	-0.037(p=0.879)	-0.209(p=0.377)	0.158(p=0.505)
	MTP power	0.199(p=0.400)	0.268(p=0.253)	0.245(p=0.297)	0.183(p=0.441)
	Ankle power	0.258(p=0.273)	0.160(p=0.502)	0.332(p=0.153)	-0.009(p=0.970)
CMJ	Jump height	0.010(p=0.967)	0.163(p=0.492)	0.010(p=0.966)	0.155(p=0.513)
	MTP power	0.175(p=0.461)	0.392(p=0.087)	0.274(p=0.243)	-0.056(p=0.814)
	Ankle power	0.080(p=0.737)	0.273(p=0.245)	0.257(p=0.274)	-0.184(p=0.438)

Table 4. Pearson product-moment correlation coefficients between anthropometric measures and performance measures for men only. * - significant correlation (p<0.01)

		ATMA	MT Length	Hallux Length	Arch Stiffness
Ankle SJ	Jump height	-0.114(p=0.633)	-0.043(p=0.859)	-0.055(p=0.817)	-0.107(p=0.654)
	MTP power	0.181(p=0.444)	0.014(p=0.955)	0.164(p=0.489)	-0.043(p=0.856)
	Ankle power	0.219(p=0.354)	0.130(p=0.586)	0.369(p=0.110)	-0.263(p=0.263)
Ankle CMJ	Jump height	-0.037(p=0.877)	-0.186(p=0.433)	-0.183(p=0.440)	0.094(p=0.694)
	MTP power	0.342(p=0.140)	0.254(p=0.280)	0.373(p=0.106)	0.102(p=0.668)
	Ankle power	0.364(p=0.115)	0.230(p=0.330)	0.486(p=0.030)	-0.148(p=0.532)
SJ	Jump height	0.151(p=0.526)	0.099(p=0.677)	0.131(p=0.581)	0.289(p=0.217)
	MTP power	0.237(p=0.313)	0.091(p=0.702)	0.258(p=0.272)	0.142(p=0.551)
	Ankle power	0.262(p=0.265)	0.186(p=0.432)	0.274(p=0.243)	0.248(p=0.293)
CMJ	Jump height	0.113(p=0.637)	-0.099(p=0.678)	0.014(p=0.954)	0.118(p=0.620)
	MTP power	0.243(p=0.302)	0.050(p=0.843)	0.347(p=0.134)	0.021(p=0.931)
	Ankle power	0.240(p=0.307)	0.068(p=0.776)	0.242(p=0.305)	0.209(p=0.376)

Table 5. Fishers exact test p values between ASJ and SJ, ACMJ and CMJ for each correlation between anthropometric variables and jump performance reported for all participants. * - significant correlation (p<0.01)

		ATMA	MT Length	Hallux Length	Arch Stiffness	
Ankle SJ	Jump height	0.116	0.453	0.312	0.258	SJ
	MTP power	0.490	0.645	0.561	0.254	
	Ankle power	0.362	0.696	0.568	0.076	
Ankle CMJ	Jump height	0.944	0.960	0.920	0.631	CMJ
	MTP power	0.667	0.373	0.711	0.833	
	Ankle power	0.703	0.465	0.575	0.234	

Fisher's LSD pairwise comparisons revealed that peak negative MTP power was larger in magnitude in males than females (p=0.009). Fishers LSD pairwise comparisons also revealed that peak negative MTP power was significantly different between SJ and ASJ (p<0.001) and ACMJ (p=0.002); however, no other significant differences were observed across conditions.

Multivariate backward linear regression results supported the conclusion that sex was the only significant contributor to jump performance (Table 6). For all conditions, models containing the variable sex alone was significant and adding additional variables (ATMA, MT length, hallux length, and arch stiffness) did not improve the overall predictability.

Table 6. Final Model Summaries for Backwards Regressions Predicting Jump Height By Condition. ***** - model significant ($p < 0.01$). ATMA, Hallux length, MT length, Arch stiffness, and Sex were included in the initial model, but only sex was left in the final model. β is based off the variable Sex and in reference to females.

Jump Condition	R^2	Adjusted R^2	β	Variables Included in Model	Model Significance
ASJ	0.190	0.169	0.436	Sex	**0.005***
ACMJ	0.485	0.472	0.697	Sex	**< 0.001***
SJ	0.433	0.418	0.658	Sex	**< 0.001***
CMJ	0.325	0.307	0.570	Sex	**< 0.001***

Chapter 5: Discussion

The aims of this study were to investigate relationships among common foot anthropometric measures and jump performances and whether movement complexity influences these relationships. Our results showed that certain performance variables (jump height, ankle joint power, MTP) were correlated with ATMA, hallux length, and MT length in certain conditions, but this was not consistent throughout all conditions. However, considering results from the ANOVA and multivariable backward linear regression results, clearly shows that performance differences where drive by sex.

We hypothesized that a longer hallux length would result in increased jump height and peak ankle joint power. Although hallux length was in fact positively correlated with ankle power across all our participants, there was no significant relationship between hallux length and jump height. Also, when separating participants by sex we did not find any of these relationships among any of the jumping conditions. The MT lengths and hallux lengths that we measured can be compared to measurements from Baxter et al. due to similar internal measurement methods (Baxter et al., 2011). MT length for our male subjects were on average 10 mm smaller than those of the participants in Baxter et al.’s study. This is most likely due to the fact that our measurements were based on a projection of the MT in the transverse plane, whereas they used a true length measure (Baxter et al., 2011). For hallux length, our males had similar values (only 4 mm smaller) than Baxter et al. (2011). Results from previous studies have shown that longer toes are related to improving performance in sprinting (Baxter et al., 2011) and jumping (van Werkhoven & Piazza, 2017b). For example, Baxter et al. (2011) found that sprinters had longer toe lengths compared to non-sprinter control subjects. These results were specifically found when separating groups by athletic ability in a non-correlation study using only males. Van Werkhoven and Piazza (2017b) found a positive relationship between toe length and jump height during an ankle only jump. Even though this was a correlational study, the relationship was found using ten male subjects only. Sex differences have been previously shown to exist in jump performance (Hawley, 2016). For example, Hawley (2016) also found a positive correlation when looking across a group of subjects (combined men and women) which is similar to our results. However, when Hawley separated results based on sex, those correlations were not consistent to the correlations across all subjects (Hawley, 2016). Of all these studies, Hawley (2016) used the largest sample size compared to 16 subjects by Baxter et al. (2011) and 10 subjects by van Werkhoven and Piazza (2017b). It is unclear why we saw differences compared to previous studies, but sample sizes, sex differences, and group differences could potentially explain differences in findings.

We hypothesized that there would be a positive correlation between ATMA length and ankle peak joint power and jump height. We found relationships between ATMA and jump height, peak ankle joint power, peak negative MTP power. However, these relationships disappeared when participants were separated by sex. Our average ATMA length for males was 49.9 mm, 8.8 mm smaller than ATMA lengths found by Baxter et al. (2011) using similar internal methods of measurement. There are different theories on the effect of ATMA on powerful movement performance. Baxter et al. (2011) suggested that a smaller ATMA allows the ankle muscles to operate at a lower velocity, thereby improving force production. However, in a later study, Baxter and Piazza (2014) showed that regardless of movement speed, participants with longer (not shorter) ATMA were able to produce more joint torque in an isokinetic dynamometer. We did not find similar results in our correlations. Again, Baxter et al. (2011) used sixteen subjects split equally between sprinters and non-sprinters, while Baxter and Piazza (2014) used an isolated ankle joint motion in a dynamometer. Similarly, van Werkhoven and Piazza (2017b) found a positive correlation between ATMA length and jump height in an ankle only jump with a similarly small sample size of 10, only male subjects. Conversely, Hawley (2016) found no correlation between ATMA length and jump height when using both males and females. It appears that differences in groups, sexes, and modality of testing are critical factors that makes generalization of results difficult.

We are unaware of any other study that has tried to correlate arch stiffness and jump height. We hypothesized that increases in arch stiffness would result in increasing jump height due to increasing the rigidity and the effectiveness of the lever of the foot. We did not find any relationship between arch stiffness and jump height. Some past research has investigated the possible relationship between arch height and jump height (Greene, McGuine, Leverson, & Best, 1998; Hawley, 2016; Zhoa et al., 2017). A similar measurement of the arch of the foot characterized by supination has been found to have a relationship with jump height (Greene et al., 1998). Greene et al. (1998) found, that in young male basketball players, that players characterized as supinated jumped higher than pronated individuals. This correlation was found investigation 115 subjects that consisted of both males and females, but only found the relationship in the males. Zhoa et al. (2017) found no relationship with jump height. This investigation was performed on 67 male subjects (Zhoa et al., 2017). Hawley (2016) also investigated the relationship between arch height and jump height and found no relationship. This study sample of subjects were closest to ours including 40 males and females. We failed to find a relationship between arch stiffness and jump height. It is possible that larger sample sizes closer to Greene et al. (1998) of 115 subjects are necessary to evaluate the true relationship between arch stiffness measures and perforce. Our method to measure arch stiffness needs to be addressed. Williams et al. (2001) previously used a camera method, similar to ours to measure arch height. They did not measure arch stiffness. The use of a camera to detect small differences in navicular height between the two conditions (10% loaded and 90% loaded) might not be a sensitive enough measure, and could explain our lack of results. The medial longitudinal arch of the foot is complex structure that hasn't been fully investigated.

Perhaps the central finding of this study is that men and women are different, and that sex seemed to be a better predictor of jump performance than foot anthropometry. This finding was shown through our ANOVA results as well as multivariable linear regression results. However, within the sexes there were also no relationships to be found. In summary, most of the past research that has found correlations between performance and foot anthropometry has been using only males (Baxter et al., 2011; van Werkhoven & Piazza, 2017b). However, some studies that have involved both males and females haven't found correlations across all subjects, but in just one sex (Greene et al., 1998), or even different correlations when comparing all participants vs one sex (Hawley, 2016). This is revealing that there are true differences between males and females. In our results, as seen in Figure 4, we had a bimodal distribution in our correlations showing males to jump higher than females, and that males in general had larger anthropometric measures. Previous research has also shown males to be bigger, have more lean muscle mass, stronger, and jump higher than females (Hawley, 2016); McMahon, Rej, & Comfort, 2017). Stature and muscle size may play a bigger role in jump performance than differences in in foot anthropometry.

In general, our results did not support any of our hypothesis, and furthermore our results were different from previous work. The possible reasons for this, along with possible limitations of our study needs to be addressed. The sample size of 40 subjects is greater than some studies that have investigated relationships of jumping and foot anthropometrics (Baxter et al., 2011; Lee & Piazza, 2009; Tanaka et al., 2017; van Werkhoven & Piazza, 2017b). Sample sizes comparing differences between trained and untrained individuals and correlations have been 10 or less in each group (Baxter et al., 2011; Lee & Piazza, 2009; Tanaka et al., 2017). Smaller sample sizes may have revealed correlations but have not truly representing their population. Our sample size was comprised of the general population and comprised both males and females. Relationships between foot anthropometry and performance that have previously been found were found in athletes versus untrained individuals (Baxter et al., 2011). Since these groups are identified based on the different characteristic of the subject pools, there appears to be a greater possibility of finding such differences in various parameters such as foot anthropometry. The main aim of this study was to find general relationships among the general population, without controlling for potential confounding factors – for example, we did not control for activity level or sport involvement. Not controlling for these may be the reason why relationships are more difficulty to establish.

In conclusion, results from this study showed that movement complexity had no significant effect on relationships between foot anthropometry and jump performance. Importantly, sex differences should be considered when evaluating foot anthropometric relationships with jump performance. To our knowledge this is the first study to investigate the effects of movement complexity on these relationships. Future research should consider much larger sample sizes. Also, controlling for potential confounding factors such as activity levels, sex, etc. appears to be critical. However, studies focusing on one specific group, for example men only, make it difficult to generalize. Only once many studies have been performed on many different groups could one perhaps understand the underlining mechanisms that links foot anthropometry to jump performance, if such a link truly exists.

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