

MUSCLE-TENDON UNIT FUNCTION DURING
CONTINUOUS AND MAXIMAL HOPPING

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by
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Abstract

MUSCLE-TENDON UNIT FUNCTION DURING CONTINUOUS AND MAXIMAL HOPPING

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Efficiency is essential for conservation of energy among all species of animals, including humans. The purpose of the present study was to determine the amount of power contributed by the triceps surae muscle complex and Achilles tendon individually during low-force, continuous hopping in comparison to a maximal hop to determine the amount of power restored to the system by the tendon via stored strain energy. Five males were recruited between the ages of 22 and 34 (age = 25.2 ± 4.97 years, mass = 77.8 ± 11.4 kg, height = 1.81 ± 0.08 m). Subjects were placed on a custom-made sled at a 10-degree angle and used their right ankle for all testing where their corresponding knee was completely immobilized, and their left leg was bent and resting on the sled. Thus, all movement was isolated to that single ankle joint and corresponding propulsive unit (triceps surae muscle complex). Subjects were fitted with 16 retro-reflective markers placed in specific anatomical locations. An ultrasound probe was placed on the triceps surae muscle complex with the superficial and deep aponeuroses visible in parallel. First, subjects were asked to perform three trials with two-minute breaks of a countermovement hop in which they were asked to maximally plantarflex

their ankle prior to an eccentric and maximal concentric contraction while the force-time curve was recorded from the corresponding force plate. Subjects were then asked to hop continuously for 15 minutes while data were collected. Net power was determined by adding the negative and positive power of the MTU, tendon, medial gastrocnemius, and soleus. The MTU was found to have significantly different positive, negative, and net power ($p \leq 0.05$) between hops where net power was found to be significantly lower during the continuous hop. The tendon was found to have significantly different negative and net power ($p \leq 0.05$) between hops where net power was found to be significantly lower during the continuous hop. The medial gastrocnemius was found to have a significantly lower net power ($p \leq 0.05$) while the soleus was found to have significantly higher negative power ($p \leq 0.05$) during the continuous hop in comparison to the maximal hop. A higher negative power during the eccentric phase allowed energy to be stored in the MTU for release of positive power during the concentric phase of the hop, resulting in a net power value closer to zero, indicative of an efficient movement where energy is conserved and not lost within the MTU energy system. The hypothesis of this study that stored strain energy from the tendon would be responsible for the majority of power and energy restoration cannot be supported. Further investigation of corresponding EMG values would be able to provide more information as to whether energy is stored or dissipated by the muscle complex for reuse by the muscle-tendon unit.

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Chapter 1: Introduction

Efficiency is essential for conservation of energy and survival across all species of animals, including humans, but the energy system dynamics used vary drastically. Several models of muscle-tendon unit (MTU) function during various locomotor tasks have been presented in previous literature, including two primary theories, which involve motor-driven and spring-driven systems (Abbott et al., 2019; Sutton et al., 2019). Concerning the force-velocity curve, motor-driven systems heavily depend on muscular force production, while spring-driven systems require an extreme velocity using stored elastic energy (Longo et al., 2019). Repetitive task models of locomotion typically favor spring actuated models. A spring-latch model is normally observed in smaller animals, involving a muscular contraction to load and store elastic energy in the tendinous structure to be released to launch the animal in the air (Astley & Roberts, 2014; Longo et al., 2019). Larger animals tend to use motor-driven systems during everyday movement because they naturally have larger muscles that can produce more work than if primarily using elastic energy (Sutton et al., 2019). However, during a repetitive locomotion task, the MTUs begin to apply a reflex circuit that uses more elastic energy in an attempt to lower energy consumption (Marques et al., 2014). It's important to note that neither model exclusively uses the muscles or tendinous structures when producing work. These models follow a spectrum according to animal size, as shown in a study observing various mammals (Lee et al., 2014). Humans are of many species known to have traveled long distance by foot, which was reliant upon the efficiency of our MTUs in the legs. Our muscles are responsible for completing the majority of locomotion task requirements. However, the work produced by the tendon is non-negligible. The tendon is

responsible for utilizing strain elastic energy stores to increase adeptness of movement during repetitive tasks for prolonged fatigue in the corresponding muscle/s. Humans use a stretch shortening cycle during jumping tasks that can be described as a combination of an eccentric contraction (active lengthening) or an isometric contraction directly followed by a concentric contraction (active shortening) that is used to ultimately increase force production within the lower body (Fukutani et al., 2015). The stretch-shortening cycle is heavily utilized during exercise and sport, while the efficiency of this movement is vital for optimal performance. Efficiency can be described as the conservation of energy during a specific locomotion task and can be improved based on target goals. By isolating the MTU of the posterior lower leg during a submaximal protocol, we can find the point where the MTU can produce force with peak efficiency. The current investigation will determine the amount of work produced in the triceps surae muscle complex and Achilles tendon and attempt to uncover which model is utilized during a repetitive submaximal human locomotion task when performance is most efficient.

The triceps surae muscle complex is the main structure responsible for ankle plantarflexion, which can be characterized by the action of pushing your forefoot into the ground, producing force. A study concluded that the angle of the knee does not affect ankle plantarflexion capabilities (Sale et al., 1982). This muscle complex consists of both the medial and lateral heads of the gastrocnemius muscle, originating from their corresponding femoral condyles, and the soleus muscle, originating from the fibula and medial line of the tibia, working collectively for force potentiation (Kümmel et al., 2018). “The Achilles tendon is the strongest and thickest tendon in the body” and attaches the muscle complex to the calcaneus forming the MTU of the posterior lower leg and allowing the contraction of the muscles to proximally raise the heel (Doral et al., 2010; O'Brien, 2005). This MTU is used during actions as simple as the muscular contractions

required to balance while standing still and more complex movements such as jumping and running. The Achilles tendon inserts these three muscle heads into the calcaneus, allowing for variations in each muscle to individually, and thus collectively, contribute to changes in the stretch-shortening cycle effect. Since all three muscle heads insert into the Achilles and each muscle varies in characteristics and functionality, non-uniform loading of the tendon is inevitable and can make it difficult to standardize conclusions of its performance (Arndt et al., 1998). This structure has to acclimate to many different velocities and forces during active stretching in jumping activities, requiring thorough investigations of how it reacts to a variety of locomotion tasks. The soleus has a high resistance to fatigue even during consistent countermovement jumps that require force production within the ankle, knee and hip joints due to its constant nature of contractions and composition of majority slow twitch fibers (Chamberlain & Lewis, 1989; Feng et al., 2011). The gastrocnemius is the largest muscle of the lower leg and produces the majority of force required to plantarflex the foot and is typically made up of a mix of slow and fast twitch muscle fibers (Sandmann et al., 1998). Many studies have observed the interaction between muscles and tendons of the whole leg or lower leg without isolation during various jumping tasks but many have not isolated the lower leg to observe its reactions independently (Hollville et al., 2019; Hollville et al., 2020; König et al., 2018; Pentidis et al., 2019). By stabilizing and limiting the movement of the knee and hip, researchers can isolate the work produced by the MTU of the posterior lower leg and through analysis, derive its efficiency and productivity when producing force during a countermovement jump.

The stretch-shortening cycle is a mechanism used during countermovement action described as an eccentric contraction followed directly by a concentric contraction, typically observed during jumping. This countermovement action can be seen during various exercises and

sports and is meant to increase jump performance. It can be characterized by greater production of force, work, and power during a concentric contraction that directly follows an isometric or eccentric contraction compared to a movement with the absence of a preceding phase (Fukutani et al., 2015; Leukel et al., 2008). The MTU takes an extensive amount of time, in reference to muscle action, causing a delay in muscular force production. A previous study from 2015 found that pre-activation, or active lengthening of the MTU, allows adequate time for increasing torque within the joint during the concentric contraction, which ultimately increases force production and overall effort (Fukutani et al., 2015). During a submaximal, repetitive hopping protocol, it is believed that the muscle will stay isometrically contracted to the best of its ability while the tendon will store and utilize elastic energy to prolong the onset of fatigue.

The difference in force potentiation during submaximal and maximal contractions can be observed through electromyography, ultrasound, and force plate measurements. When concerning maximal contractions, muscular fatigue typically sets in after a prolonged period of time. Fatigue can be observed by lower EMG values and results from the inability of the neuromuscular system to keep up with the demand for motor unit recruitment. The neuromuscular system has a direct relationship to muscular function and stiffness meaning lower function of the neuromuscular system causes lower values of muscle activation and stiffness. The lower jump performance observed in children due to their untrained neuromuscular systems can support this notion (Patikas, 2014). Although researchers found evidence of significant differences in muscle fascicle behavior during a stretch-shortening cycle, tendon behavior is not highly influenced by age (Hoffrén et al., 2012). By simply fatiguing the muscles, a lower neural drive can also be induced within adults. However, during submaximal work that does not induce major fatigue, an increase in motor unit recruitment can compensate for exhausted muscle fibers and is reflected by increased EMG

readings. The stretch reflex associated with the tendon and the force produced by the muscles are both utilized during submaximal exercise. In contrast, during maximal contractions, the contribution of the stretch reflex is nearly nonexistent. A contraction that operates similar to an isometric contraction, where the tendon elongates and shortens in response rather than the muscle, is the optimal zone for force production based on force-time curves (Fukutani et al., 2015). This type of contraction can only be produced during a submaximal effort due to the limitations of the MTU length changes.

Previous literature based on the stretch-shortening cycle induced within the triceps surae muscle complex and Achilles tendon have just begun the depths of research required to fully understand how these structure work during various jumping movements. Researchers have found inconclusive data regarding where work is produced during active stretch-shortening cycles during jumping exercise and conclude that further research is needed (Lidstone et al., 2016). A repeated submaximal hopping protocol was implemented in a study published in 2019, which found fatiguing patterns of the MTU that resulted from a decrease in muscle and tendon stiffness (Kubo & Ikebukuro, 2019). While their study employed an accurate submaximal protocol, it was only able to identify the results of exhaustion. There is a need for an actual submaximal pattern that does not fatigue the MTU to record enough data to support the notion that the Achilles tendon produces a substantial amount of work during submaximal hops because the recoil of elastic energy stored in the tendon is released into the active muscle (Lichtwark & Wilson, 2005). The relationship between muscle and tendon lengthening varies between different locomotion task requirements.

Due to locomotive task changes over multiple movements, we assume that repetitive locomotion tasks induce a motor pathway in the MTU that improves force production and thus hopping efficiency. In a study published in 2018, researchers focused on the specific tendon and muscle fascicle length changes towards the end of the eccentric phase of the stretch shortening cycle that occurred during a repetitive hopping protocol where the knees and arms were immobilized to isolate work produced by the lower leg (Lidstone et al., 2018). Researchers found that when rebounding or bouncing during the multiple hops prior to the maximal jump, the muscle fascicle length shortened over multiple hops while tendon length increased resulting in higher jump heights and supporting the conclusion that the Achilles tendon contributes work from its elastic energy storage. The current study will employ a protocol that is free of force potentiation produced by the knees and will enable us to focus on the work produced by the triceps surae muscle complex and Achilles tendon.

Efficiency of the stretch-shortening cycle is imperative for maximizing athletic performance. When athletes are required to jump various heights in order to excel within their sport, evaluation and subsequential correction of techniques utilizing the stretch-shortening cycle can mean the difference between first and second place. By isolating the work produced by the lower leg, researchers have been closer to developing conclusions on the underlying mechanics of the stretch-shortening cycle utilized within the triceps surae muscle complex and Achilles tendon. Our study focuses on the stretch-shortening cycle, repetitively induced within the ankle joint at a constant submaximal rate to better understand where power is produced within the MTU. The purpose of the current study was to determine the amount of work contributed by the triceps surae muscle complex and Achilles tendon individually during low-force, continuous hopping by

evaluating the underlying mechanisms of the stretch-shortening cycle to increase efficiency for running and jumping athletes.

Chapter 2: Methods

Subjects

Five males between the ages of 22 and 34 participated in the current study (age = 25.2 ± 4.97 years, mass = 77.8 ± 11.4 kg, height = 1.81 ± 0.08 m). All subjects were recreationally active but not trained hoppers or jumpers and were free of any cardiovascular disease and/or musculoskeletal injuries within the past year. Voluntary written consent was obtained from each subject before commencement of any testing.

Procedure

Subjects were placed on a carriage attached to rails on a customized sled at a 10-degree angle while standing on a force plate. Subjects used their right ankle for all testing and their corresponding knee was completely immobilized. Thus, all movement was isolated to that single ankle joint and corresponding propulsive unit (triceps surae muscle complex). The left leg remained in a relaxed bent position secured to the carriage. First, the subjects were asked to perform a countermovement hop in which they were asked to maximally plantarflex their ankle prior to an eccentric and maximal concentric contraction while the force-time curve was recorded from the corresponding force plate. The subjects performed three trials of this test with two minutes of rest between each trial. Then, subjects practiced hopping continuously for 2 minutes. After these practice hops, the subjects rested for 5 minutes and then asked to hop for 15 minutes while data was collected. Subjects were instructed to begin on their toes in a plantarflexed position and then

to go downwards (eccentric phase) and then upwards (concentric phase) attempting to leave the force plate and continue hopping in a self-selected pattern repetitively for the duration of the 15 minutes.



Figure 1. Image of a subject on the carriage. Their right knee is immobilized with their right calf fitted with an ultrasound probe and their lower body has 16 retro-reflective markers placed in anatomical positions

Data recording

Subjects were fitted with 16 retro-reflective markers that were placed in specific anatomical locations for motion capture. Three-dimensional motion analysis was performed by utilizing a 3D infrared 9-camera VICON motion analysis system (Oxford Metrics, Oxford, UK) and a force plate (AMTI, Watertown, USA). Motion capture data was collected at 250 Hz and force plate data was collected at 1000 Hz. In addition, an ultrasound probe (Telemed, Vilnius, Lithuania) was placed on the lateral aspect of the triceps surae muscle complex of the subject with the superficial and deep aponeuroses in parallel as ultrasound data was collected at 30 Hz.

Biomechanical analysis

A zero-lag fourth-order low-pass Butterworth filter was utilized to filter marker trajectories (11 Hz) and force plate data (14 Hz) for all locomotor tasks. Calculation of subject center of mass (COM) z-axis acceleration (axis along the length of the carriage motion along the rails of the sled) was performed by dividing the respective vertical force-time curve (minus the force associated with acceleration due to gravity) by the subject's body mass. Forward dynamics were then utilized to determine the velocity and displacement of the COM with displacement being used to determine hop height. Ensemble force-displacement curves for the COM were created by resampling all subject data to 100 Hz. Ankle moment in the sagittal plane was calculated through inverse dynamics using the motion capture kinematic data and the corresponding force plate kinetic data.

Muscle-tendon unit kinematics and kinetics

MTU length was estimated by anatomical measurements from the lateral epicondyle of the femur to the lateral malleolus of the ankle. MTU length changes were calculated using the angular displacement of ankle rotation from motion capture and the measured moment arm of the triceps surae muscle complex around the ankle. Video analysis of ultrasound imaging was performed using Kinovea open source video analysis software (Kinovea for Windows, Version 0.8.15, Kinovea.org). Pennation angle was calculated as the average of five angles measured at different positions on the ultrasound image. The muscle thickness was defined as the average vertical distance between the deep and superficial aponeuroses. This was calculated as the average of the distance between the aponeuroses on both sides of the image. Muscle length was defined as the average thickness divided by the tangent of the average of the five pennation angles. This calculated muscle length indicates the component of the triceps surae length parallel to the tendon.

Tendon length was calculated as the difference between the MTU and the muscle length. MTU force was calculated by using the measured ankle joint moment arm and the ankle joint moment. Muscle and tendon displacements were plotted against the MTU force and the area under these curves were calculated as the respective work values for the eccentric and concentric phase of the movements. Ensemble muscle and tendon force-displacement curves were created by resampling all subject data to 100 Hz. Net tendon work was simply the addition of the negative and positive work from the respective phases of the locomotor task.

Statistical analysis

Data were normally distributed, and a general linear model one-way analysis of variance was utilized for comparisons of hop height and ankle, muscle and tendon work. Pearson product correlation coefficients (r) were calculated for select variables. Statistical Parametric Mapping was implemented using a general linear model univariate analysis of variance for each set of data in the respective average force- and power-time curves to determine areas of significant difference between groups during both hops (Rice et al., 2019). All analyses were performed using SPSS (Version 24.0, Chicago, USA) and significance was chosen at p less than or equal to 0.05.

Chapter 3: Results

Average vertical ground reaction force (VGRF) curves in relative time for the continuous and maximal hops are presented and there was significant difference in VGRF between the two hops from 5 - 69% and 80 - 89% relative time (Fig. 2). Significant differences between the two types of hops are visualized by the grey areas.

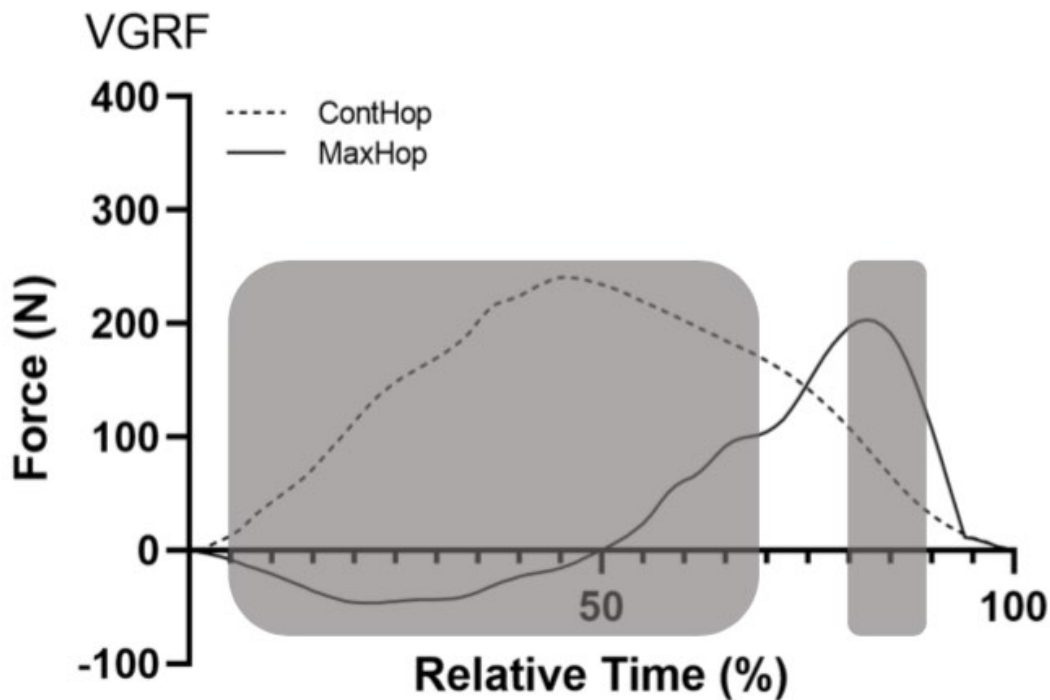


Figure 2. The average vertical ground reaction force (VGRF) curves in relative time are presented for continuous hop (ContHop) and maximal hop (MaxHop). Significant difference is indicated by the grey shaded area (≤ 0.05).

MTU negative, positive, and net power measured during the continuous and maximal hop are presented (Fig. 3). Power values were found to be significantly different between the two measured hops. The negative and positive powers of the MTU were both found to be significantly different ($p \leq 0.05$) between the continuous and maximal hop with mean values for MTU negative power during the continuous and maximal hop of $-4.6 \pm 1.5 \text{ W/kg}$ and $-0.7 \pm 0.1 \text{ W/kg}$. Mean values for MTU positive power during the continuous and maximal hop were $6.9 \pm 1.9 \text{ W/kg}$ and $12.9 \pm$

3.4W/kg. Net power of the MTU was found to be significantly lower ($p \leq 0.05$) during the continuous hop with a mean value of 2.3 ± 0.8 W/kg when compared to the maximal hop with a mean value of 12.3 ± 3.4 W/kg. Average MTU power curves in relative time for the continuous and maximal hops are presented as well (Fig. 4). There was significant difference in MTU power between the two hops from 6 - 39%, 49 - 75%, and 89 - 94% relative time.

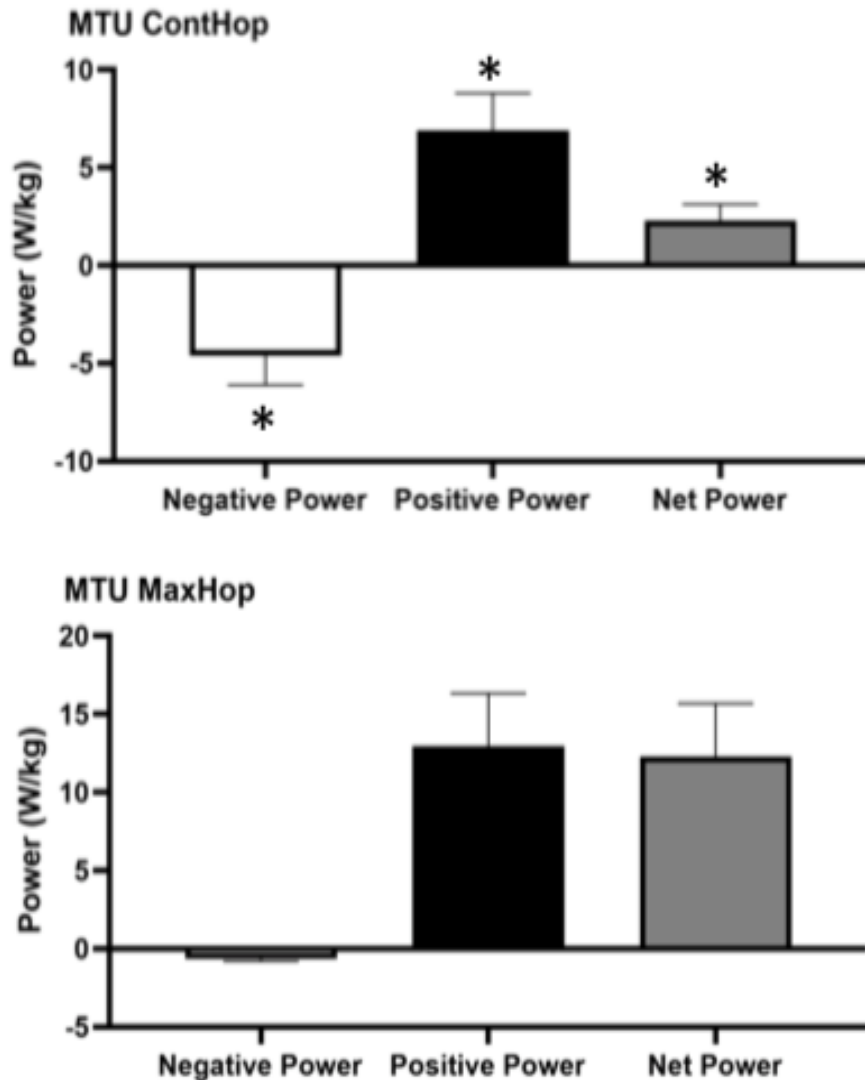


Figure 3. Muscle-tendon unit (MTU) negative, positive, and net power measured during the continuous and maximal hop. * = significant difference in power between the continuous and maximal hop ($p \leq 0.05$).

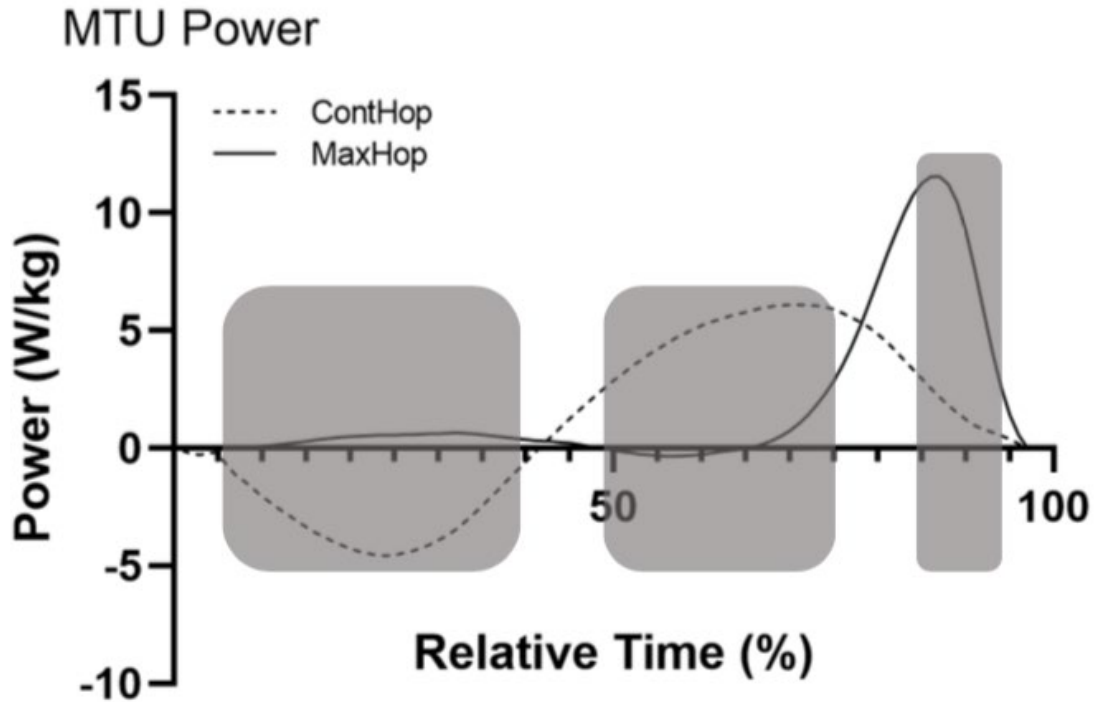


Figure 4. The average power curves in relative time are presented for continuous hop (ContHop) and maximal hop (MaxHop). Significant difference is indicated by the grey shaded areas (≤ 0.05).

Medial gastrocnemius and soleus negative, positive, and net power measured during the continuous and maximal hop are presented (Fig. 5). There were no significant differences between the two hops when regarding the negative or positive medial gastrocnemius fascicle power, however the net power was found to be significantly lower during the continuous hop with a mean value of -0.01 ± 0.3 W/kg when compared to the maximal hop with a mean value of 0.7 ± 0.6 W/kg ($p \leq 0.05$). Mean values for medial gastrocnemius fascicle negative power during the continuous and maximal hop were -0.7 ± 0.4 W/kg and -0.3 ± 0.3 W/kg. Mean values for medial gastrocnemius fascicle positive power during the continuous and maximal hop were 0.6 ± 0.5 W/kg and 1.0 ± 0.4 W/kg. Negative soleus fascicle power was found to be significantly lower ($p \leq 0.05$) during the continuous hop compared to the maximal hop with mean values of -5.1 ± 3.1 W/kg and -1.2 ± 1.0 W/kg. Mean values for soleus fascicle positive power during the continuous and maximal hop

were $6.6 \pm 5.4\text{W/kg}$ and $4.6 \pm 4.1\text{W/kg}$. Mean values for soleus fascicle net power during the continuous and maximal hop were $1.5 \pm 2.5\text{W/kg}$ and $3.4 \pm 4.4\text{W/kg}$. Average medial gastrocnemius power curves in relative time for the continuous and maximal hops are presented (Fig. 6). There was significant difference in medial gastrocnemius power between the two hops from 26 - 31% relative time. Average soleus power curves in relative time for the continuous and maximal hops are presented as well and there was significant difference in soleus gastrocnemius power between the two hops from 39 - 52% relative time (Fig. 7).

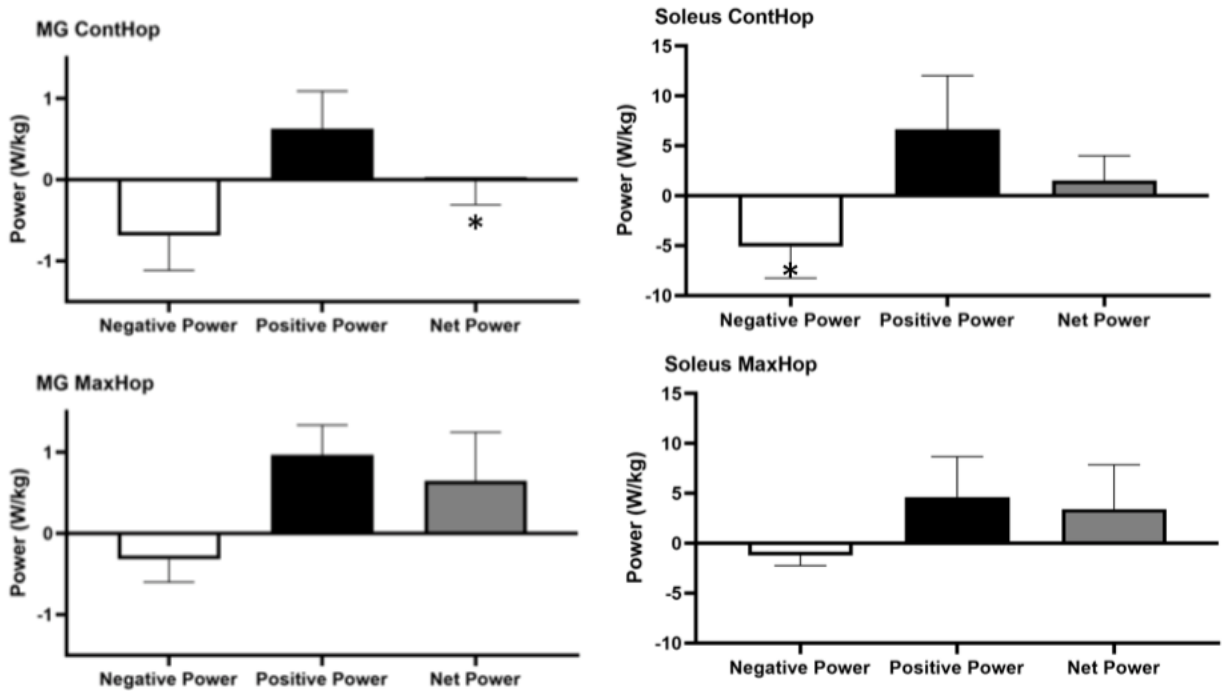


Figure 5. Medial gastrocnemius and soleus negative, positive, and net power measured during the continuous hop (ContHop) and maximal hop (MaxHop). * = significant difference in power between the continuous and maximal hop ($p \leq 0.05$).

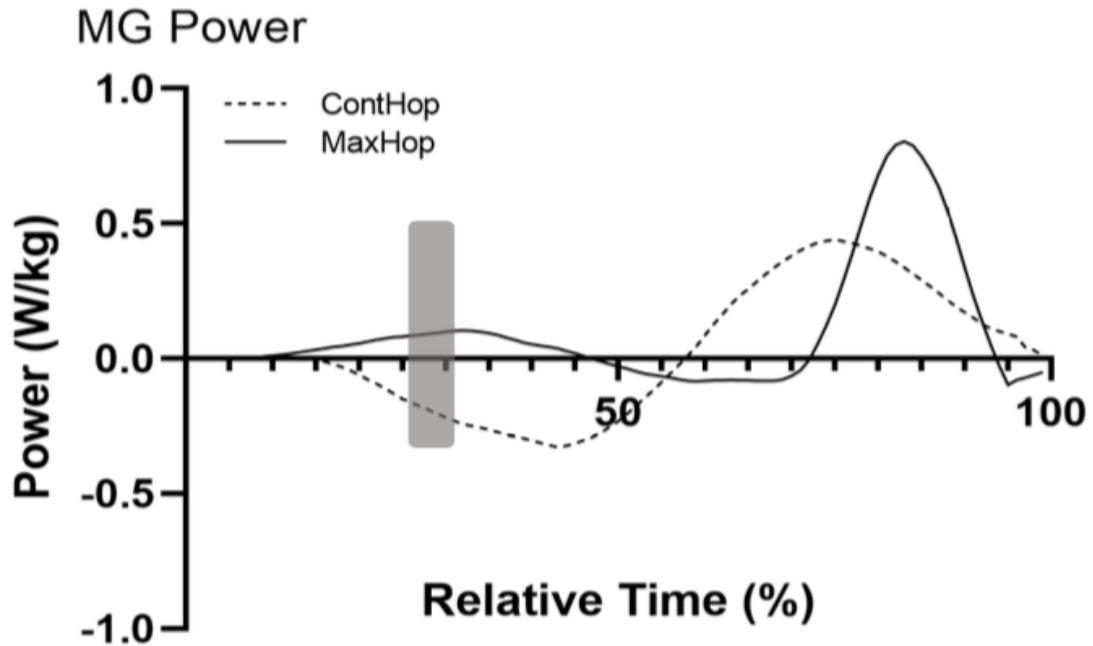


Figure 6. The average medial gastrocnemius (MG) power curves in relative time are presented for continuous hop (ContHop) and maximal hop (MaxHop). Significant difference is indicated by the grey shaded area (≤ 0.05).

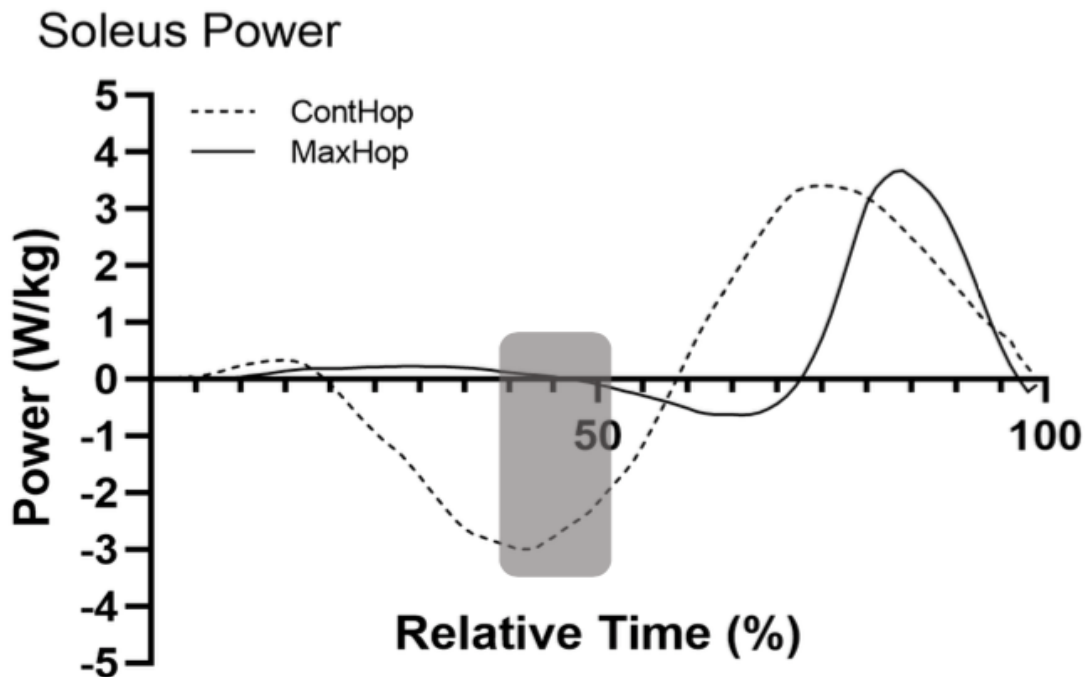


Figure 7. The average soleus power curves in relative time are presented for continuous hop (ContHop) and maximal hop (MaxHop). Significant difference is indicated by the grey shaded area (≤ 0.05).

Tendon negative, positive, and net power measured during the continuous and maximal hop are presented (Fig. 8). The differences in negative power of the tendon was found to be non-significant between the two hops although positive power of the tendon was found to be significantly different ($p \leq 0.05$). Mean values for tendon negative power during the continuous and maximal hop were 1.2 ± 3.1 W/kg and 0.9 ± 1.2 W/kg. Mean values for tendon positive power during the continuous and maximal hop were -0.3 ± 4.5 W/kg and 7.4 ± 4.3 W/kg. The net power of the tendon was found to be significantly lower ($p \leq 0.05$) during the continuous hop with a mean value of 0.8 ± 1.9 W/kg when compared to the maximal hop with a mean value of 8.3 ± 4.8 W/kg.

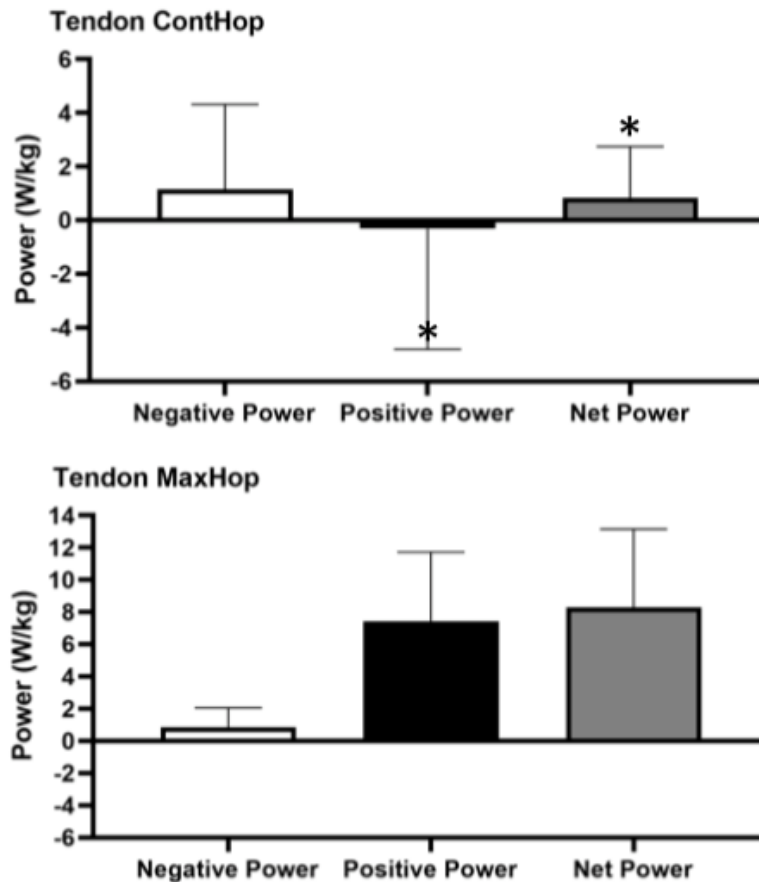


Figure 8. Tendon negative, positive, and net power measured during the continuous and maximal hop. * = significant difference in power between the continuous and maximal hop ($p \leq 0.05$).

Chapter 4: Discussion and Implications

The purpose of the current study was to determine the amount of power contributed by the triceps surae muscle complex and Achilles tendon individually during low-force, continuous hopping and the amount of power restored to the system by the tendon via stored strain energy. By evaluating the MTU during a continuous and maximal hop, comparisons of the subsequent power were made to determine the difference in efficiency of tendon energy restoration. The hypothesis of this study, stored strain energy from the tendon would be responsible for energy restoration cannot be supported based on the overall lack of tendon power. We can assume that energy was stored and released from the muscles of the triceps surae complex itself however, based on our results, we could suggest that energy was dissipated through the eccentric phase and recovered by either the muscle or tendon during the concentric phase of the continuous hop. Previous studies have observed this phenomenon of energy dissipation by the muscle which in turn is absorbed for release by the tendon (Konow et al., 2012; Konow & Roberts, 2015; Roberts & Konow, 2013). Werkhausen et al reported muscles dissipate energy during eccentric contraction during an increased stretch of the Achilles tendon with higher loads or added mass with increased stretch of the medial gastrocnemius and soleus allowing for more energy contribution of elastic elements of the MTU (Werkhausen et al., 2017). EMG values obtained in the current study could provide more information as to whether the energy was stored or dissipated by the muscle complex for reuse.

The primary finding of this investigation was that net power was measured to be significantly lower, or closer to zero, in the continuous hop when compared to the maximal hop,

indicating a more efficient hop where energy is conserved and not lost to the MTU energy system. VGRF during the continuous hop was proportionally equal throughout the eccentric and concentric phases of the hop allowing negative power to increase during the eccentric phase subsequently decreasing net power. Whereas in the maximal hop, subjects allowed themselves to “drop” from the plantarflexed position, apply minimal force and thus negative power until they reached the end of the eccentric phase where they quickly applied force and increased positive power to jump as high as possible, making net power increase in return. Negative power during the eccentric phase allowed energy to be stored in the MTU to release positive power during the concentric phase of the hop and was due to pre-stretch of the muscle, increasing mechanical efficiency (McBride & Snyder, 2012; McCaulley et al., 2007). Eccentric movements reduced energy cost during the stretch shortening cycle, as stated in another study (Biewener & Roberts, 2000). While muscle fascicle length changes were more apparent in the maximal hop, assumptions can be made that this was due to the subjects jumping considerably higher than during the continuous hops since tendon power was minimal throughout the continuous hop.

The MTU of the lower leg was observed in a previous study during maximal hops where subjects were dropped from various heights and asked to immediately jump and found similar results where the MTU used active muscle work to produce force off of the force plate (McBride, 2021). The presence of a pre-hop found the MTU conserves energy within the system and in turn, lower net work. Their findings were similar to the current study’s findings of a lower net power by recycling energy within the MTU system (Aeles et al., 2018). Elastic energy redistribution only accounted for 16% of work performed during a hopping task performed on one leg (Lichtwark & Wilson, 2005). This research further proves that tendon elastic energy stores are not entirely responsible for the spring-like behavior expressed during continuous hopping as hypothesized by

our study. Elastic energy stores usage may also depend of muscle fiber types as indicated in a study where slow twitch muscle fibers used approximately 24% of elastic energy from the tendon whereas fast twitch fibers used only approximately 17% (Bosco et al., 1982). Further studies should examine the muscular fiber properties of the triceps surae muscle complex prior to examination between different hopping locomotion tasks.

As with all research, this study had limitations. A limitation to acknowledge in the current study may include the sample size of five subjects where interpretation of the results could be limited. Using a two-tailed t-test to achieve an effect size of at least 0.8 and a power greater than 0.95, a sample size of at least twenty-three subjects must be tested when replicating this study as stated by G*Power (Faul et al., 2007). Due to the anatomy of the lower leg and the soleus existing deep to the gastrocnemius, while imaging of the soleus is not impossible, it is more difficult to capture, thus causing more variations between viable subject measurements. The soleus muscle was found to be non-significant between hops which may have been caused by limited visibility in the ultrasound when the muscles were contracted. Although there were many non-significant findings between powers, these values still followed a consistent trend, indicating a study with a larger sample size would more than likely find additional significant differences between their hop values.

Future investigations should also consider studying the same research topic with a larger sample size of at least twenty-three subjects to increase statistical power found by G*Power (Faul et al., 2007). With the many modalities of measurement used in the current study, our sample size decreased by almost three quarters because the guarantee of adequate data to analyze was incredibly difficult and there could potentially be options to minimize these issues in the future.

Furthermore, future studies should consider studying hops of the same altitude rather than a continuous submaximal hop that reaches lower heights compared to the single maximal hop. By standardizing the height of the both types of hops, more informative data could be deduced as to whether the tendon provides more strain energy restoration during hops that are meant to be “efficient” in comparison to a maximal effort hop. Due to the angle of the sled, the subjects may have been hopping at a rate slower than needed, where a previous study states that hopping rates at 2.2 Hz or higher, the MTU of the lower leg acts as an elastic spring (Farley et al., 1991). This can be seen in the current study; however, we cannot assume the elastic spring movement is due to the tendons strain elastic energy stores. We can assume that energy was conserved during active muscle contraction via ATP driven myosin, actin and titin interaction (Squire, 2019).

The findings of both muscle-tendon unit models, motor-driven and spring-driven, being used in human locomotion in the current study can further add to knowledge-based improvements for sport performance. Muscular strength is the forefront of improvements in performance whether a task requires submaximal or maximal effort. Understanding that the triceps surae muscle complex and Achilles tendon act as a spring due to energy restoration within the muscle will help coaches improve endurance training in athletes by strengthening the muscles. Plyometric training involves explosive and reactive movements where power is vital for performance. Strength training should be utilized in addition to plyometric training to improve force potentiation among velocity improvements for maximized muscular power. These findings also promote the idea that prosthetic limb developers should begin constructing limbs that automatically switch between spring-driven and motor-driven systems. Humans use spring-driven systems for repetitive, endurance-based movements such as walking and running and motor-driven system for

movements such as stair climbing or fall mitigation. Creating a limb that can automatically switch between either system, people will no longer have to have multiple prosthetics for different tasks.

Chapter 5: Conclusion

In conclusion, subjects reached an “efficient” hop during the submaximal hopping protocol although it was not due to tendon energy restoration as hypothesized. Net power was found to be closer to zero in all variables during the continuous hop when compared to the maximal hop. This was due to more negative power being produced during the eccentric phase with positive power being produced in the concentric phase of the hops. Minimal negative and positive power were produced within the tendon during the continuous hop resulting in a lower net power. Our study suggests that subjects used active muscle contractility during both the continuous and maximal hops however, it can be assumed by our data that energy was stored and in turn released into the MTU by the muscles themselves during the continuous hop. The MTU acted as a spring to ultimately decrease net power produced, implying a more efficient movement where energy is not lost. Humans are not subjected to either the spring-driven or motor-driven system but use either system depending on task requirements. The information gained from this study could further improve endurance sport performance, plyometric training, and even prosthetic limb development.

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Vita

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