EFFECT OF COUNTER-MOVEMENT FREQUENCY ON PERFORMANCE IN A SINGLE JOINT MAXIMAL HOPPING TASK

A Thesis
by
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Abstract

EFFECT OF COUNTER-MOVEMENT FREQUENCY ON PERFORMANCE IN A SINGLE JOINT MAXIMAL JUMPING TASK

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Optimal performance in a maximal jumping task occurs when a countermovement is utilized prior to the concentric phase of the movement. Performance augmentation results from the near isometric behavior of the fascicles and storage of elastic energy in tendon structures. It has been suggested that Stretch Shortening Cycle (SSC) tasks should be performed at resonant frequency for optimal performance and mechanical efficiency in both cyclical and maximal SSC tasks. Resonance frequency has been defined as the frequency at which the highest muscle-tendon unit to contractile component length ratio (MTU:CC) occurs. Furthermore, previous research has shown that in a maximal single joint hopping task, multiple counter-movements (mCM) produces better performance compared to single counter-movements (sCM). Previous research has proposed that the augmented performance in subjects utilizing a mCM strategy in a single joint hop is from making use of mechanical resonance facilitating elastic storage in the tendon. ***Purpose:*** The current study has three main purposes: (1) to determine if maximal hop height occurs at resonance frequency, (2) to test if mCM produces higher hops compared to the sCM, and (3) to examine effect of counter-movement number on the MTU:CC amplitude ratio between the mCM and sCM condition. ***Subjects:*** Seventeen healthy male subjects (age: 23.8±4 years, height: 1.76±0.1m, weight: 79.7±16.3kg, MVIP: 2197±556N) were recruited for the study. ***Methods:*** Subjects performed bounces at 6 pre-determined frequencies (2, 2.3, 2.66, 2.93, 3.33, 3.46Hz) while ultrasound of the medial gastrocnemius muscle and kinematic marker data were used to calculate the muscle-tendon unit to contractile component ratio length change ratio (MTU:CC). The frequency at which the MTU:CC ratio was highest was defined as resonance frequency. Subjects performed nine maximal height mCM hops and nine sCM hops. MTU:CC ratios were calculated between jump conditions. Hop heights in both conditions were calculated using flight time. ***Results:*** We were unable to determine resonance frequency for all subjects from highest MTU:CC ratio. However, subjects performed the final bounce in mCM at a frequency not significantly different from the natural oscillation frequency (p= 0.78). Difference between CM frequency and natural frequency was strongly negatively correlated in both conditions with maximal hop height (sCM: r = - 0.599, mCM: r = - 0.6). Subjects achieved higher hop in the mCM compared to the sCM condition (p= 0.01). MTU:CC ratio was higher in the final bounce in mCM compared to sCM (p = 0.015). CC length was significantly shorter in mCM final bounce compared with sCM (p = 0.003). ***Conclusion:*** The current study arrived at four main conclusions: (1) we were unable to determine resonance by the MTU:CC ratio alone; (2) maximal SSC performance occurs at natural oscillation frequency; (3) subjects performed maximal height hop when performing mCM; and (4) performance augmentation in mCM can be attributed to enhanced elastic storage in tendon resulting from a shorter operating CC.

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Introduction

Both computational models and experimental protocols using human subjects have reported that a counter-movement prior to push-off produces optimal performance in a maximal jumping task (Earn, Kraemer, Prue, Volek, Carl, Joseph, & Newton., 2011; Kubo, 1999; Kubo, Morimoto, Komuro, Tsunoda, Kanehisa, & Fukunaga., 2007; Nagano, Komura, & Fukashiro, 2004). The performance increases result from greater storage of elastic energy in tendon structures and release of that energy in the following concentric contraction of the muscle. Elastic recoil of the tendon occurs at a high velocity enhancing power and jump height (Fukashiro, Kurokawa, Hay, & Nagano., 2005).

In-vivo studies using ultrasound technology during stretch-shortening cycle activity have directly measured the behavior of the muscle-tendon unit (MTU) (Fukashiro, Hay, & Nagano, 2006; Kubo, Kanehisa, & Fukunaga, 2001; Takeshita, Shibayama, Muraoka, Muramatsu, Nagano, Fukunaga, & Fukashiro, 2006). Principle findings of these studies show that during the eccentric phase of the counter-movement jump, the muscle fascicles remain in a quasi-isometric contraction and shorten at low velocity (Finni, Ikegawa, Lepola, & Komi, 2003; Fukashiro, Kurokawa, Hay, D.C., & Nagano, 2005; Kubo , Takeshita, Fukashiro, & Fukunaga, 2000). Due to the muscle force-velocity relationship, the near isometric muscle length allows for a high level of force production, while the tendon contributes to concentric power through elastic recoil (Fukunaga, Kawakami, Kubo, & Kanehisa, 2002). Furthermore, this results in decreased length change in the contractile component (CC) which reduces the fascicles contribution to MTU length change. During cyclical activities, the behavior of the MTU enhances mechanical efficiency through the large contribution of the tendon to work performed (Fukashiro et al., 2006; Lichtwark & Wilson, 2005; Nagano, Fukashiro, & Komura, 2003; Takeshita et al., 2006). The behavior of the MTU during cyclical stretch-shortening cycle (SSC) exercise is, however, frequency dependent (Dean & Kuo, 2011; Kubo et al., 2000; Nagano et al., 2003; Takeshita et al., 2006). During cyclical ankle plantar flexion exercise, Takeshita et al. (2006) found that at intermediate frequencies (2.67-3Hz) the amplitude of the MTU length change compared to fascicle length change is greatest. The frequency at which this occurs is considered resonance and is characterized by a large contribution of tendon structures to work output during the SSC task. When the MTU performs cyclic movements at resonant frequency, the fascicles behave isometrically, allowing high muscle force with low shortening velocity. This behavior is favorable due to the force-velocity and force-length relationship. The tendon, on the other hand, acts as a compliant spring that recovers elastic energy.

The tendency of a mechanical system to absorb more energy when the frequency of its oscillations matches the system's natural frequency is termed resonance. The frequency at which resonance occurs is termed resonance frequency. Resonance and natural frequency are the same frequency for a mechanical system, since resonance occurs when a spring oscillates at natural frequency. To optimize elastic storage in the tendon and achieve resonance, the applied force from the plantar flexors should be in tune with the natural frequency of the system. When the MTU is an 'optimally tuned spring' at resonant frequency, the tendon is responsible for most of the MTU length change resulting in maximized elastic energy storage (Robertston & Sawicki, 2014). Failure to perform maximal SSC movements at natural frequency has been associated with the SSC action being ineffective in enhancing concentric performance (Wilson, Murphy, Walshe, & Ness, 1996). The current study will attempt to determine if maximal hop performance occurs at natural frequency.

The large movement amplitude of the tendon during cyclic plantar flexion could potentially store and release higher levels of elastic energy in the tendon compared to a sCM. In a study by van Werkhoven and Piazza (2013), performance during a single joint hop was found to be optimal when using a multiple counter-movement strategy. Van Werkhoven and Piazza hypothesized that a mCM strategy resulted in greater storage of elastic energy during a maximal single joint hop when compared to a sCM. They did not, however, measure muscle behavior directly with ultrasound to determine whether differences existed with respect to MTU length occurred between sCM and mCM strategies. The implementation of a mCM strategy could potentially result in a greater MTU:CC length ratio compared to a sCM. This finding would indicate greater contribution of tendon to total MTU length change and more isometric behavior of the fascicles. To the best of our knowledge, there is no research examining the relationship between plantarflexor muscle resonance and its effect on performance in a maximal height hop. Furthermore, the movement frequency at which maximal jump performance occurs has not been compared to the resonance frequency of the task. The current study will attempt to fill this gap within the literature. The current study has three main purposes: (1) to determine if maximal hop height occurs at resonance frequency, (2) to test if mCM produces higher hops compared to the sCM, and (3) to examine effect of counter-movement number on the MTU:CC amplitude ratio between the mCM and sCM conditions. We hypothesize that (1) maximal height hop performance will occur at resonant frequency, (2) using multiple counter-movements will result in superior jump performance compared to a to a single counter movement, and (3) a higher amplitude ratio between the MTU and CC will occur during mCM trials compared to sCM trials.

Review of Literature

Introduction

Critical analysis of the literature will allow for a greater understanding of the relevant research previously conducted on SSC performance. The literature presents these themes in a variety of contexts; however, this review will focus on their application to a maximal single joint hop. Previous research examining the effect of using a counter-movement prior to push-off has demonstrated that superior jump performance results from this strategy. The use of a counter-movement makes use of potential energy storage in passive structures and contributes to jumping power. Furthermore, the use of multiple counter-movements prior to push-off may result in greater performance in a maximal single-joint hop. We have proposed that greater storage of elastic energy in the Achilles tendon and higher muscle activation, when using a mCM, will elicit greater hop performance. The current study will attempt to measure the in-vivo behavior of the fascicles during both maximal sCM and mCM ankle joint jumps in addition to other possible mechanisms contributing to performance. This literature review will examine current knowledge on MTU behavior during SSC exercise, resonance frequency during ankle bouncing, mEMG responses during SSC exercise, and the effect of mechanical properties of the MTU on SSC performance.

MTC Behavior & SSC Exercise

Series elasticity contributes greatly to work performed during SSC exercise. In analyzing the MTU behavior at the ankle joint, the high contribution of the Achilles tendon to jumping or hopping performance is primarily from the storage and release of elastic energy through the process of elastic recoil. In a study by Fukashiro et al., (2005), the fascicular and tendinous behavior of the gastrocnemius (MG) during a vertical ankle jump (AJ) and a drop jump (DJ) were measured in-vivo (Fukashiro et al., 2005). Their findings suggested considerable contribution of tendon to jump performance. During the push-off phase of the AJ, the tendon contributed 47% of the work performed by the MTU and 75% in the DJ. During the DJ the Achilles tendon (AT) returned 76% of the elastic energy stored. Of interest is the low amplitude of length change that occurs in the muscle fascicles during the DJ. During the push-off phase of the DJ, the fascicles shortened 2mm while the tendon shortened rapidly by 24mm. The quasi-isometric contraction of the fascicles during the downward (plantar flexion) phase increases strain on the tendon and significantly contributes to the jump height through elastic recoil. In accordance with the force-velocity curve, by shortening at a low velocity, the fascicles are able to generate higher force while the rapid shortening of the tendon contributes to power production. Although this study did not include a counter-movement jump trial, it provides insight into in-vivo MTU behavior during a SSC.

In addition, Lichtwark and Wilson (2005), measured MTU length change during a one-legged hopping task and reported similar results to Fukashiro et al. (2005). They reported that the AT contributes 80% of the total MTU length change throughout a hopping cycle. Furthermore, the AT was stretched in proportion to the force applied in the downward phase and returns 74% in the upward movement contributing a total average of 16% of mechanical energy to the hopping task. Furthermore, the muscle was found to stretch only a small amount resulting in a more energy efficient movement.

Finni et al. (2003) also reported similar MTU behavior during unilateral counter-movement jumps (CMJ) and drop jumps (DJ) using a sled apparatus. They measured patella tendon force and muscle fascicle length change of the vastus lateralis (VL) using ultrasound imaging. It was reported that during fast SSC (DJ) exercise the high neural input reduces muscle fascicle lengthening, contributing to AT strain. In the DJ, the muscle EMG was higher than in the CMJ, resulting in a lower magnitude of fascicle length change and higher tendon force and shortening speeds. The fascicle shortening velocity was 8.6 ± 4.2 and 2.8 ± 2.8 cm $\sin^{-1}$ CMJ and DJ, respectively. These values show that the fascicles in the DJ are remaining in a more isometric contraction and are better able to produce higher forces shortening at lower velocities. The increase of mEMG during the DJ increases muscle stiffness due to higher exercise intensity and reduces the velocity of the muscle fascicles thereby enhancing force production capability. This low fascicle shortening velocity during SSC exercise was also reported in Kubo et al. (2000). Kubo et al (2000) reported that during the transition from dorsi to plantar flexion in fast cyclical

SSC exercise, there was a rapid increase in the velocity of tendon structures (82.9 ± 17.3mm s^{-1}) with a comparatively lower velocity of the fascicle (16.3 ± 17.1mm s^{-1}) (Kubo et al., 2000). MCMs performed at a fast frequency could result in higher shortening velocity and elastic storage in the tendon resulting in superior performance compared to a sCM.

In similarity to Finni et al. (2003), Kubo et al. (2007) analyzed single-joint jump performance using a squat jump, CMJ, and DJ in human subjects. However, Kubo et al. (2007) examined MTU behavior at the Achilles tendon rather than the patellar tendon. They reported that mEMG of the m. gastrocnemius in the eccentric phase was significantly higher in the DJ than the CMJ resulting in higher tendon force (Kubo et al., 2007). This implies that tendon elasticity plays a greater role in enhancing jump performance when higher forces are generated in the eccentric phase of the jump. In the CMJ lower forces are produced by the muscle fascicles due to greater magnitude of lengthening, and lower mEMG compared to the DJ. The eccentric mEMG during the DJ is higher than in the CMJ, thus contributing to greater isometric muscle force and storage and release of elastic energy. MCMs could potentially make better use of tendon elasticity if greater mEMG and muscle stiffness were to result from this movement strategy. Multiple CMs could potentially allow more time for the fascicles to generate higher force when compared to a single CM.

Kurokawa, Fukunaga, Nagano, & Fukashiro (2003), reported similar results to those mentioned above, however, they found no observed lengthening of the fascicles in the downward phase of a maximal CMJ. In the downward phase, the fascicles shortened by 10.4% and the tendon structures lengthened by 2.2%. The results indicated that potentiation from the stretch-reflex likely did not occur since the fascicles underwent no eccentric lengthening during the maximal CMJ. This is in contrast to the aforementioned studies that reported an eccentric length change in the fascicles during a CMJ. Perhaps a multiple CMJ could allow more total length change of the MTC and elicit greater stretch of the m. gastrocnemius resulting in a stretch reflex. It should also be noted that the stiffness and hysteresis of the subjects AT were not measured in this study.

Resonance and SSC

Mechanical resonance is defined as a movement frequency characterized by a large contribution of tendon structures to mechanical work (Takeshita et al., 2006). Furthermore, the tendency of a mechanical system to absorb more energy occurs when the frequency of its oscillations matches the system's natural frequency. To optimize elastic storage in the tendon and achieve resonance, the applied force from the plantarflexors should be in tune with the natural frequency of the system. The current study will attempt to determine if the frequency at which the MTU:CC ratio is maximized (indicative of maximized energy storage in the tendon) is related to the natural frequency determined by the free-oscillation method. Research has reported several average frequencies at which mechanical resonance is achieved during cyclical SSC exercise (Bach, Chapman, & Calvert, 1983; Dean & Kuo, 2011; Kubo et al., 2000; Lichtwark & Wilson, 2005; Nagano et al., 2003; Takeshita et al., 2006; van Werkhoven & Piazza, 2013). An early study by Bach et al. (1983), reported average resonant frequency was 3.33 ± 0.15Hz in human subjects during a bouncing task at the ankle joint. Another study reported that at 3Hz, efficiency was highest (45 ± 15%) with most of the work being performed during a bouncing task by the SEC (Dean & Kuo, 2011). Dean and Kuo (2011) analyzed bouncing frequencies ranging from 1 to 4Hz with highest metabolic energy expenditure being recorded at the lowest and highest frequencies. These results suggest that at frequencies not associated with resonance, muscle is performing most of the work with higher energy expenditure. In addition, the highest EMG amplitude was observed at intermediate or resonant frequency (3.07 ± 0.43Hz). As mentioned in the previous section, higher muscle activation increases the stiffness of the muscle and allows higher tendon strain and storage of elastic energy.

Nagano et al. (2003), found similar results to the aforementioned study with higher bouncing frequencies resulting in the greatest contribution of the SEC to positive mechanical work output of the MTU during the push-off phase of a bouncing task. This study employed a 2-dimensional computational model of the human body to perform the plantar flexion task at two movement frequencies (1.33Hz and 3.33Hz). When the model performed the cyclical bouncing task, the SEC contributed 47% at 3.33Hz with only a 3% contribution observed at 1.33Hz. Furthermore, higher muscle activation was observed in the downward phase at the faster movement frequency (3.33Hz).

To gain a better understanding of the MTU dynamics during different movement frequencies, Takeshita et al. (2006) used real-time ultrasound imaging to investigate the behavior of the MTU during an ankle bouncing task at eight frequencies (1.33 to 3.67Hz). They found that the behavior of the MTU depended on the movement frequency selected. In similarity to Dean and Kuo (2011), they reported resonance to occur at an intermediate frequency (2.67Hz), with work output of the contractile component minimized. They found that at higher frequencies, the fascicles varied more out of phase with the MTU. In other words, as the MTU was lengthening, the fascicles were shortening at higher frequencies. At 3Hz, the highest amplitude ratio between the MTU and fascicle was observed illustrating that tendon is responsible for most of the length change of the MTU at this intermediate frequency.

During a maximal mCM hop, it would be expected that optimal performance would correspond to resonant or intermediate frequencies. This would result in the greatest amplitude of tendon lengthening and storage and release of elastic energy contributing to jump performance. However, individual characteristics of the MTU, including tendon compliance and stiffness, could result in a vast range of resonant frequencies in movement and ultimately in variable jump performances between subjects. Subjects may not self-select frequencies that correspond to resonance.

It appears that individual self-selected bouncing frequency could be based on limiting energetic cost rather than resonance frequency (Merritt, Raburn, & Dean, 2010). Merritt et al. (2010) had their subjects perform seven ankle bouncing trials to a metronome at (1, 1.5, 2, 2.25, 2.5, 2.75, 3Hz). The subjects then performed three trials at their preferred bouncing frequency. Subjects did not bounce at their resonant frequency, but rather at significantly lower frequencies. The researchers proposed that although bouncing at resonant frequency is the most mechanically efficient strategy, a slower frequency may have been selected as it may require minimal energetic cost. Therefore, instructing subjects to perform a maximal jump using mCMs using a preferred bouncing frequency could diminish performance if they select a frequency where the muscle is not operating at near-isometric length. A multiple CM performed at a frequency close to resonance should hypothetically contribute most to a maximal jump due to optimal loading of the tendon and the ideal isometric conditions for the muscle to produce high force.

Van Werkhoven and Piazza (2013) used a computational model and human subjects to determine the optimal strategy for performing a maximal-height single joint hop. Although they did not directly measure MTU behavior during the jump, they determined that the optimal strategy involved using multiple CMs. Four of the subjects who jumped highest performed mCMs at a frequency of 2.53±0.47Hz, which is close to the frequency associated with resonance found in the aforementioned studies. Other subjects who failed to jump highest using mCMs bounced at a frequency of 1.46±0.45Hz. The subjects who utilized a mCM jumped 18.7±4.5cm while non-bouncers jumped 13.9±3.3cm. Multiple bounces performed at natural oscillation frequency should maximize the length of the MTU and favor elastic storage in the tendon. Takeshita et al. (2006) reported that when bouncing close to resonant frequency, the tendon amplitude compared to the fascicle is highest. The in-vivo behavior of the MTU during a maximal-height hop using mCMs still requires investigation. The current study will attempt to fill this gap within the literature.

EMG responses during SCC activity

At resonant frequency, the muscle remains in a quasi-isometric contraction with large amplitude tendon lengthening. Furthermore, during SSC exercise at resonance, the EMG amplitude is highest and relatively higher muscle activation is found in the downward phase (Dean & Kuo, 2011; Nagano et al., 2003; Takeshita et al., 2006). This pattern of activation allows the tendon to contribute most to the MTU length change and storage of elastic energy. In contrast, at lower movement frequency, high EMG is observed in the plantar flexion phase rather than earlier in dorsi-flexion (Kubo et al., 2000; Nagano et al., 2003; Takeshita et al., 2006). High amplitude mEMG early in dorsi-flexion is desirable since high muscle activation during eccentric loading increases muscle force and storage of elastic energy, both of which contribute to concentric power. Increasing work performed in the eccentric phase will also lead to more energy efficient movement.

Kubo et al. (2000), defined slow frequency at 0.3Hz and fast at 1.0Hz whereas low and high frequency was described as 1.33Hz and 3.33Hz respectively by Nagano (2003).

Furthermore, the lowest frequency analyzed by Takeshita et al. (2006) was 1.33Hz, with the highest being 3.67Hz. Therefore, the lowest frequencies recorded in these studies (Nagano et al., 2003; Takeshita et al., 2006) are higher than the highest frequency recorded in Kubo et al. (2000) even though 1.0Hz was described as being superior to 0.3Hz in terms of mEMG of the gastrocnemius (GAS). This data demonstrates that mEMG of the GAS is frequency dependent and mEMG appears earlier in the dorsi-flexion phase as bouncing frequency increases. In high intensity SSC activities such as a Drop Jump (DJ), muscle activation occurs early in ground contact with a forceful stretch reflex contribution that stimulates greater muscle force and greater storage of elastic energy in the MTC (Gollhofer, Strojnik, Rapp, & Schweizer, 1992). Furthermore, in the CMJ, mEMG is higher than in the SJ contributing to greater jump height (Kubo et al., 2007). These findings demonstrate that mEMG during jumping is also intensity dependent with DJ resulting in the highest mEMG response. Muscle activation in the gastrocnemius is therefore frequency and intensity dependent. The increase in muscle activation and stiffness results in the rapid lengthening and recoil of the tendon. This enables higher force production and velocity during the push-off phase of jumping.

MTU stiffness and SSC performance

Van Werkhoven & Piazza (2013) reported that the frequency of mCMs prior to a maximal single joint jump increases with higher tendon stiffness in addition to reduced jump performance. Mechanical properties of the tendon are important measures to better understand the underlying mechanisms that allow for optimal SSC performance. A more compliant tendon stores and utilizes elastic energy better than a stiff tendon. This was observed in Kubo (1999), where pre-stretch augmentation during a CMJ was significantly greater in the group with more compliant tendons compared to the group with stiffer tendons. The subjects in the study were divided into compliant (n=15) and stiff (n=16) groups. Pre-stretch augmentation in the compliant group was 13.8 ± 5.9% and 7.6 ± 2.9% in the stiff group. Furthermore, Walshe, Wilson, & Murphy (1996) found similar results, with stiff subjects displaying significantly lower pre-stretch augmentation (10.5 ± 3.3%) compared to compliant subjects (17.9 ± 5.3%), in maximal jumping. A CM therefore contributed to jump performance to a greater degree in the compliant group compared to the stiff group. It can therefore be hypothesized that use of multiple CMs will contribute a greater degree to SSC performance in those with higher tendon compliance. Similar results to the aforementioned studies were reported in Kubo et al. (2007). In their study, they measured in- vivo dynamics of the MTU of the ankle during maximal single joint jumps with tendon stiffness being significantly negatively correlated to pre-stretch augmentation in the CMJ ($r = -0.471$) and DJ ($r = -0.502$). Higher performance during a single joint maximal hop can therefore be expected in subjects with higher tendon compliance. One measure not reported in the previously mentioned studies is tendon hysteresis. Tendon hysteresis is a property of the tendon that defines the energy dissipated as heat due to its material viscosity (Finni, Peltonen, Stenroth, & Cronin, 2013) . In a study by Kubo et al. (2005), hysteresis of the Achilles tendon was found to be negatively correlated with pre-stretch augmentation, indicating that lower hysteresis values resulted in a greater stretch-shortening cycle performance (Kubo et al., 2005). Furthermore, Kubo et al. (2005), found no significant correlation between stiffness and hysteresis, indicating that a more compliant tendon (greater elastic storage capability) and less hysteresis (more return of elastic energy) is beneficial to stretch-shortening performance.

MCMs prior to bouncing could potentially enhance the total lengthening of the AT, resulting in greater overall performance. The mCMs would provide more time for the muscle to generate higher forces and stiffness, thereby increasing the stretch imposed on the tendon in the downward phase and returning more elastic energy in the push-off phase. Those subjects with low hysteresis should therefore benefit most from the use of multiple counter-movements as more of the stored elastic energy in the tendon is returned. The effect of the mechanical properties of the MTU on resonance frequency or stretch-shortening cycle performance will not be examined in the current study.

Methods

Subjects

Seventeen male subjects participated in the current study and provided informed consent. All subjects were healthy with no musculoskeletal injury, neuromuscular disease, or history of lower limb surgery. Furthermore, participants were informed of the procedures and risks associated with the study and voluntarily participated.

Table 1- Subject characteristics

	Age (yr)	**BW (kg)**	**Height (m)**	**MVIP (N)**
Subjects (n=17)	23.8 ± 4	79.7 ± 16.3	1.76 ± 0.1	2197 ± 556

Study Design

After informed consent was obtained, subject's anthropometric measurements were taken. Anthropometric measures included height, weight, and lower leg length (distance from the center of the malleolus lateralis to the articular cleft between the femur and tibia condyles). Following anthropometric measurements, subjects completed three maximal voluntary isometric plantarflexion (MVIP). The subject's stood with their knees fully extended with their feet elevated on a wooden block at a 90° ankle angle. The subjects were on the balls of their feet with a stationary bar on their shoulders. The MVIP was performed on a force plate that recorded vertical GRF. The highest recorded GRF was recorded as the subject MVIP.

Natural Frequency

Following the MVIP, each subject's natural oscillation frequency was measured using the free-oscillation method (Fukashiro, Noda, & Shibayama, 2001). Subjects stood with the balls of their feet on a wooden block with ankles at a 90° angle with a modified bar on their shoulders. A standing position was selected so that natural oscillation frequency was measured position specific to the performance-based tests used in the current study (Walshe et al., 1996). This measure provides the natural frequency of the entire ankle. The bar was incrementally loaded from 5-40 kg (Fukashiro et al., 2006), with 1 minute rest periods provided between load changes. The perturbation applied to the bar was a 10 lb medicine ball dropped from the tester's shoulder height. This provided consistent perturbations for the testing session. The subjects could not react to the perturbations applied to the bar since they occurred directly behind the subject out of their field of view, and no verbal cue was given prior to the perturbation. Furthermore, subjects were instructed to maintain their pre-determined foot position on the block for the length of each trial. Each subject's initial foot position was marked with tape on the wooden block to ensure foot position was consistent for every trial. The natural frequency was determined using the dampened force oscillation pattern. The peak-to-peak frequency of the oscillations at the eight different loads was averaged to calculate a natural oscillation frequency value for each subject.

Active Resonance

Following the standing free-oscillations, subjects performed the standing cyclical SCC task at 6 pre-determined frequencies (2, 2.3, 2.66, 2.93, 3.33, and 3.46 Hz), set to a metronome for determination of resonance frequency. These frequencies were used since they were within the range of resonance frequency for ankle bouncing reported in the literature. Resonance was defined as the frequency at which the maximal ratio of MTU length change to that of the CC length change occurs (Takeshita et al., 2006). CC length changes, calculated by tracking fascicle length changes, were measured using a Telemed Echo Blaster 128 CEXT ultrasound unit. Instantaneous MTU length was calculated from kinematic marker data. All kinetic and kinematic data were smoothed with a 10 Hz 4th order Butterworth low pass filter. The orders of frequencies were randomized, with each trial lasting 15 seconds. Subjects were given a 1 minute rest period between trials.

Maximal Height Hops

Following the resonance frequency test, subjects performed bilateral standing CMJs using only the ankle joint to perform the task. Subjects wore a knee brace on each leg to eliminate movement at the knee joint (Dean & Kuo, 2011). Participants were instructed to perform single CMJs at 3 frequencies – a self-selected (SS) frequency, as well as 0.5Hz below self-selected and 0.5Hz above SS frequency. After self-selected frequency hops were completed, the average of the three SS frequencies were calculated, and subjects performed 0.5Hz above and below SS frequency. This range of frequencies was used in order to move subjects closer to resonance in case they self-selected frequencies that were not near their resonance frequency. Subjects were instructed to perform a maximal height hop without bending their knees. Furthermore, the order of trials (sCM or mCM) was randomized. Each jump was separated by a 2 minute rest period with a 5 min rest period between frequency changes. The mCM consisted of subjects performing three mCMs at the prescribed frequency (SS, 0.5 above, and 0.5 below) prior to push-off. Jumps were performed on a force plate, and GRFs were collected for every trial at 1000 Hz using a BNC-2010 interface box with an analog-to-digital card (National Instruments, NI PCI- 6014, Austin, Texas, USA). In addition, four retro reflective markers (fifth metatarsophalangeal joint, the lateral malleolus, the lateral epicondyle of the knee, the greater trochanter) on each leg were tracked real-time using 3D Videography (Vicon Nexus, Centennial, CO, USA), consisting of seven MX03+ NIR cameras at a frequency of 100Hz using infrared detection of optical markers.

For collection of each trial, the Vicon system was started first, with the ultrasound system activated immediately after. Once both systems were activated, the subject was instructed to begin the trial (bounce or jump trial). A sync signal sent by the ultrasound to the Vicon system allowed for real time analysis of ultrasound video, GRF, and motion analysis.

Measurement of MTU and fascicle length change

The ultrasound probe was secured to the surface of the skin on the left leg with Nexcare™ Athletic Wrap and athletic tape at 30% of the lower leg length to obtain a longitudinal image of the MG (Kubo et al., 2001; Kurokawa, Fukunaga, & Fukashiro, 2001). The probe was placed at the mid-muscle belly with the superficial and deep aponeuroses in parallel as viewed on the ultrasound image. The probe was then rotated 90º in line with the mid-longitudinal fascicle plane (Bénard, Becher, Harlaar, Huijing, & Jaspers, 2009). Fascicle angle (α) was defined as the angle between the fascicle and deep aponeurosis. Fascicle angle (α) was the average of three fascicle angles arranged on the deep aponeurosis. The height was defined as the vertical distance of the deep and superficial aponeuroses. This was calculated as the average of distance between the aponeuroses on both sides of the image. Contractile component (CC) length was defined as

$$CC_{length} = height_{(AVG)} / \tan(\alpha)_{(AVG)}$$

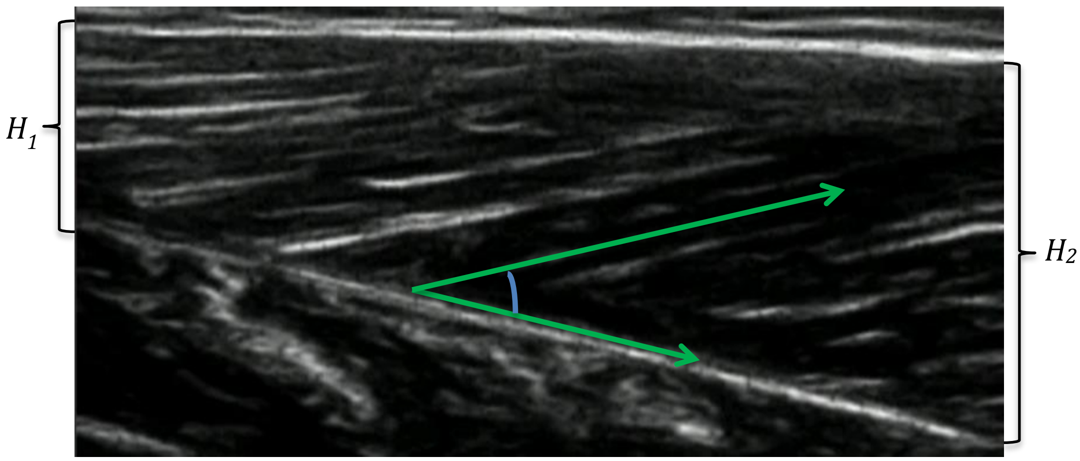

Figure 1- Medial gastrocnemius ultrasound imaging

The instantaneous length of the MTU was calculated using the equations of Grieve et al., (1977).

$$L_{MTC} = L_l\,(-15.72217 + 0.30141 + A_j - 0.00061 \cdot A^2_j)$$

A_j and L_l are the ankle-joint angle and lower leg length (distance from the center of the malleolus lateralis to the articular cleft between the femur and tibia condyles), respectively (Kubo et al., 2000). Instantaneous changes in ankle angle were calculated using 3D videography. MTU:CC length was calculated using the averages of maximal and minimum CC length.

Data Selection and Exclusion Criteria

For bouncing trials, 5 cyclic bounces (peak to peak plantarflexion) following 10 seconds of movement initiation were selected for analysis. Movement initiation was defined as the point at which the subject moved from peak plantarflexion to dorsiflexion at the start of the trial. The average CC length at the peak plantarflexions and dorsiflexions were subtracted from each other to determine CC length change. The same method was used to calculate length change in the MTU. This information was then used to determine the MTU:CC ratio for determination of resonance.

For the maximal hop trials, a knee angle exceeding 15º from each subject's collected static trial was excluded from analysis. Once all the trials exceeding the exclusion criteria were determined, the highest jump recorded in the sCM and mCM trials were analyzed. Jump height was calculated using the time in air (TIA) method calculated as the period between take-off and contact after flight.

Each subject's maximal sCM and mCM trials were analyzed for CM frequency, and ultrasound was used to determine fascicle length from each jump. The CM time in both conditions was measured as the time from the downward movement initiation peak to the end of the downward movement phase multiplied by two. The inverse of time was the frequency of the CM. In addition the MTU:CC ratio was calculated for the end of each CM in the maximal hop trials (mCM and sCM).

Statistics

The general linear model with repeated-measures analysis of variance and post hoc tests were used to determine changes in MTU:CC ratio, MTU length, and CC length between all three CMs (Bounce 1, Bounce 2, Bounce 3) in the mCM condition and sCM trial. Within group differences for each condition were assessed through a general linear model with repeated measures analysis of variance. Post hoc tests were used to determine the locations of any differences between the conditions (sCM, Bounce 1, Bounce 2, Bounce 3). The assumptions for a linear model were met, and statistical significance for all analyses was defined by $p = \leq 0.05$. All statistical analyses were performed using SPSS version 12.0 (SPSS Inc., Chicago, Ill). Paired T-Tests were used to assess differences in hop heights between conditions and frequencies.

Results

Resonance & Maximal Hop Frequency

We were unable to determine whether resonance frequency occurred at any one of the 6 pre-determined frequencies. Although bouncing frequency increased, the amplitude ratio did not change (Figure 1 and Table 1). For this reason the null hypothesis that there would be no significant difference in frequency between resonance frequency, determined by maximized amplitude ratio and maximal hop CM frequency, must be rejected. This method may not be accurate in determining at which frequency resonance occurs. We did not find that resonance occurred at the 3Hz reported by Takeshita et al. (2006) using the MTU:CC amplitude ratio. None of the amplitude ratios at the various frequencies were significantly different from each other except those shown below. There was no difference in the amplitude ratio between the lowest frequency (2Hz) and the highest frequency (3.46Hz).

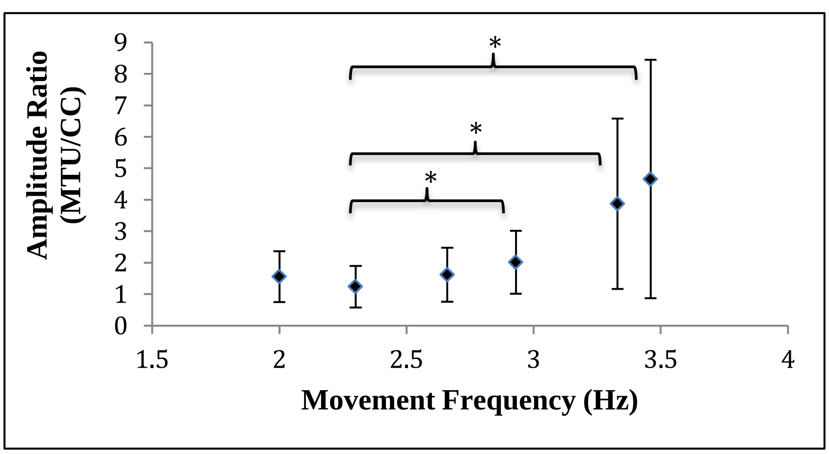

Figure 2- Average MTU:CC ratios at each pre-determined frequency; **p value* $\leq$ *0.05*

Table 2- MTU:CC ratios at pre-determined frequencies;*p value ≤ 0.05

MTU:CC Ratio	**Mean ± SD**	**2Hz**	**2.3Hz**	**2.66Hz**	**2.93Hz**	**3.33Hz**	**3.46Hz**
2Hz	**1.55 ± 0.81**		0.48	0.6	0.34	0.07	0.1
2.3Hz	**1.23 ± 0.66**	0.48		0.198	0.03*	0.026*	0.029*
2.66Hz	**1.61 ± 0.86**	0.6	0.198		0.16	0.06	0.06
2.93Hz	**2.01 ± 1**	0.34	0.03*	0.16		0.199	0.06
3.33Hz	**3.87 ± 2.7**	0.07	0.026*	0.06	0.199		0.68
3.46Hz	**4.65 ± 3.79**	0.1	0.029*	0.06	0.06	0.68	

It has been proposed that resonance occurs at a systems natural frequency. Therefore, natural frequency could be a more accurate measure of resonance frequency. Fifteen subject's natural oscillation frequency data was also used to determine if they performed the maximal hop CM at their natural frequency. Two subject's data was removed from analysis due to unusable data. The average CM frequency for the maximal hop trials was 2.93 ± 0.4Hz and 1.96 ± 0.51Hz for the mCM and sCM hops, respectively. When using the natural frequency of the ankle joint as a measure of resonance, there was no significant difference between resonance and mCM frequency ($p = 0.78$) (Figure 2). The results indicate that subjects performed the last CM in the mCM condition at their natural frequency as determined by the free-oscillation method. A significant difference still existed between the natural oscillation frequency and sCM ($p=.0001$). The natural frequency reported in the current study was 2.96 ± 0.21Hz. This was similar to the average natural frequency found by Takeshita et al. (2.84 ± 0.18Hz), and Dean & Kuo (3.1Hz).

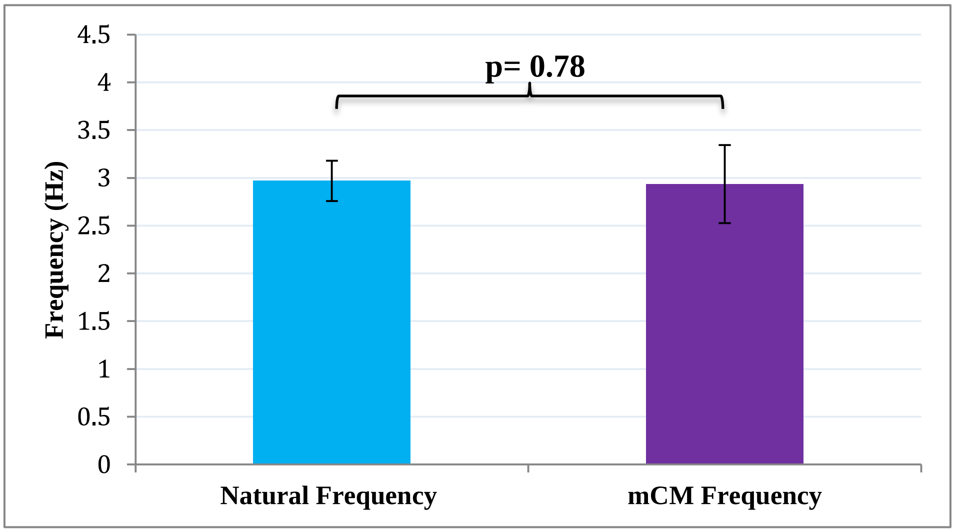

Figure 3- Natural frequency vs. mCM frequency

Table 3- Natural frequency, sCM, and mCM

Frequency (Hz)	**Mean±SD**	**sCM Hz**	**mCM Hz**
Natural Oscillation Frequency	2.96 ± 0.21Hz	*P*= 0.0001*	*P*= 0.78
mCM Frequency (Bounce 3)	2.93 ± 0.4Hz		
sCM Frequency	1.96 ± 0.51Hz		

The frequency difference between subject's mCM and sCM frequency and their natural frequency was strongly negatively correlated with hopping height (sCM, r= - 0.599 p = 0.018; mCM, r = - 0.6 p = 0.018) for both conditions (Figure 4 and 5). This finding shows that when subjects performed the mCM closer to their natural frequency, hop performance was augmented.

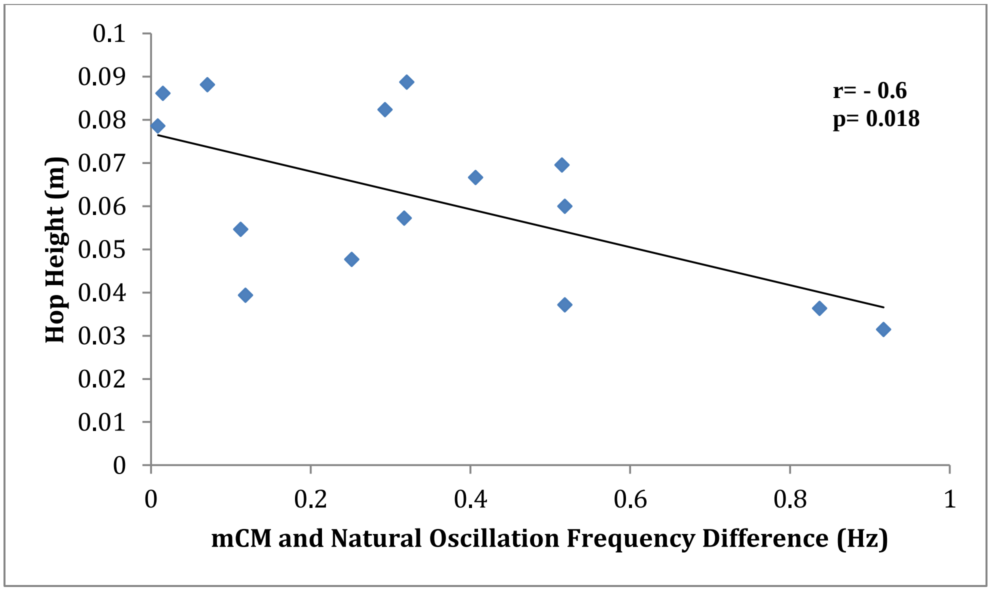

Figure 4- Frequency difference between mCM and Natural Frequency

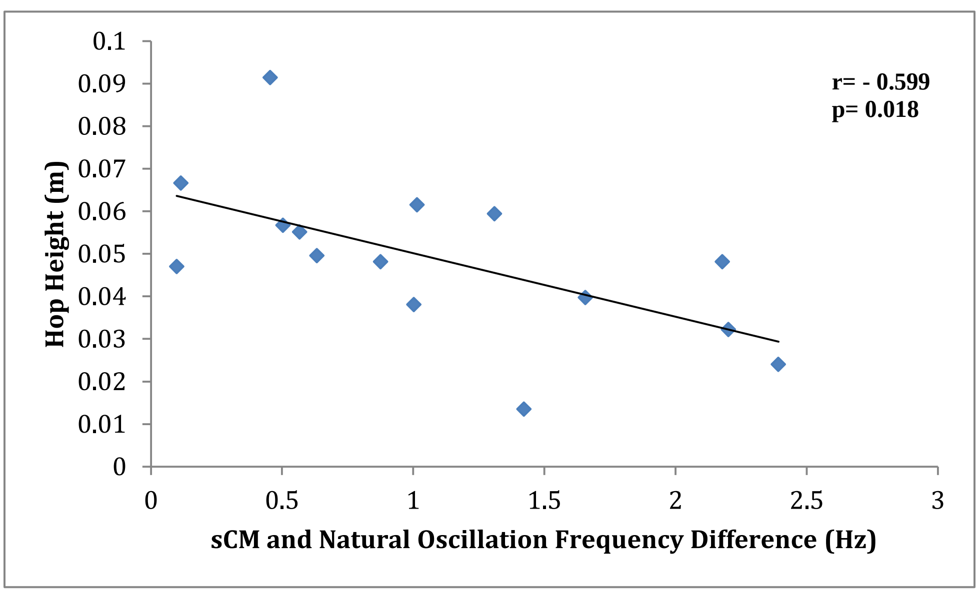

Figure 5- Frequency difference between sCM and Natural Frequency

Maximal Hop Height

All seventeen subject's data was used to determine if mCM produces significantly higher hop heights compared to sCM. It was determined that subjects hopped significantly higher ($p = 0.01$) in the mCM (0.059 ± 0.02m) condition compared to in the sCM (0.047 ± 0.01m). The augmented performance in mCM compared with sCM could be attributed to the subject's making use of mechanical resonance by performing the CM at their natural oscillation frequency. To test if the differences in hop height were from differences in knee angle, we examined the relationship between hop height and knee angle. Average knee angle in the mCM and sCM were 9.84 ± 3.33 and 8.7 ± 3.14 degrees respectively, from their reference static trial. There was no significant difference in knee angle between the sCM and mCM ($p = 0.221$) and no significant correlation (sCM, $r = 0.354$ $p = 0.164$, mCM, $r= 0.349$ $p = 0.169$) between knee angle and maximal hop heights. It can therefore be concluded that knee angle was not responsible for differences in hop heights within subjects. Furthermore, absolute MVIP (sCM, $r = 0.064$ $p = 0.806$; mCM, $r= -.028$ $p = 0.915$) and body weight relative to (sCM, $r = 0.303$ $p = 0.237$; mCM, $r = 0.264$ $p = 0.306$) MVIP did not significantly correlate with maximal hop height

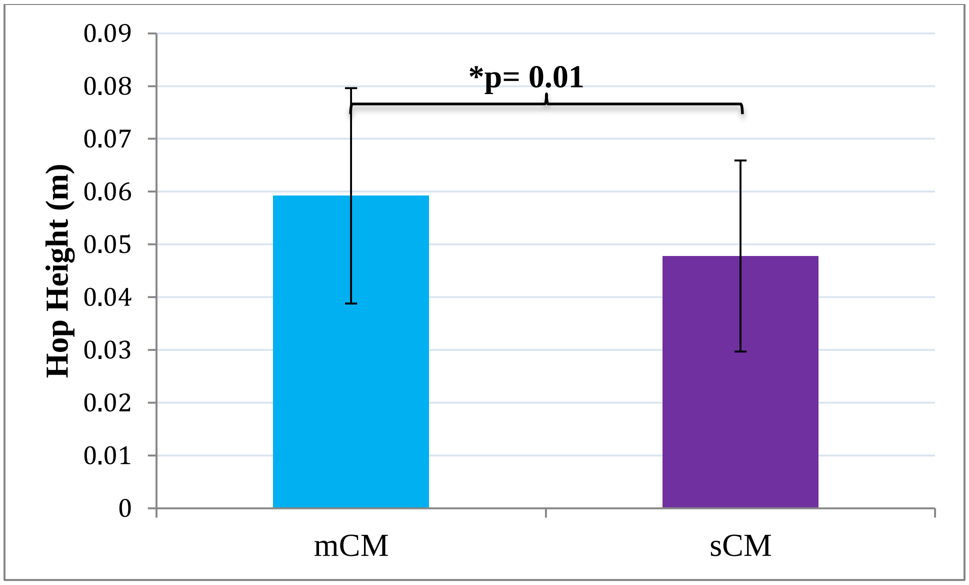

Figure 6 - Hop height difference between hop conditions

Table 4- Mean hop heights in mCM and sCM

	Hop Height (m)
mCM	0.059 ± 0.02
sCM	0.047 ± 0.01

Muscle-Tendon Unit Behavior in sCM vs mCM

In order to determine the underlying mechanisms contributing to the performance increase between the sCM and mCM, the amplitude ratio of the MTU and CC was analyzed at peak dorsiflexion of each CM. Within subjects the MTU and CC length changes would provide insight on their relationship to maximal performance. A repeated measure ANOVA was run on all 4 conditions and MTU:CC length ratio, contractile component length, and MTU length and significance was found at $p = 0.003$. Bounce 1 was the first counter-movement, bounce 2 was the counter-movement between bounce 1 and 3, and bounce 3 was the final counter-movement before take-off. In the sCM, only one bounce was performed, so it is termed sCM.

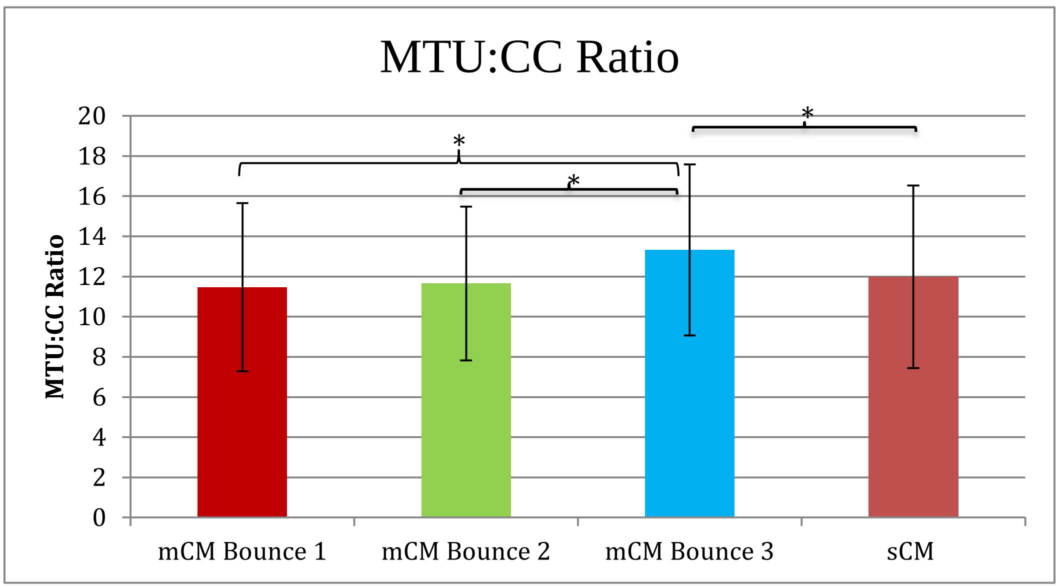

Figure 7 - MTU:CC Ratio in each CM

Table 4 - *p value* $= \leq 0.05$

	MTU:CC	**Bounce 1**	**Bounce 2**	**Bounce 3**	**sCM**
Bounce 1	11.47 ± 4.18		0.351	0.000*	0.236
Bounce 2	11.65 ± 3.82	0.351		0.000*	0.511
Bounce 3	13.32 ± 4.25	0.000*	0.000*		0.015*
sCM	11.99 ± 4.54	0.236	0.511	0.015*	

The MTU:CC length ratio was significantly higher in the mCM final CM across all conditions. Although the ratio between Bounce 1 and Bounce 2 was not significant, changes in MTU length and CC length could show enhanced elastic storage in the tendon between the two bounces. At Bounce 3, elastic storage was significantly higher than the sCM. The higher MTU:CC ratio indicates higher elastic storage and is most likely responsible for the augmented performance in mCM compared with sCM. The results demonstrate that elastic storage is optimized when subjects perform the CM at their natural oscillation frequency making use of mechanical resonance of the tendon.

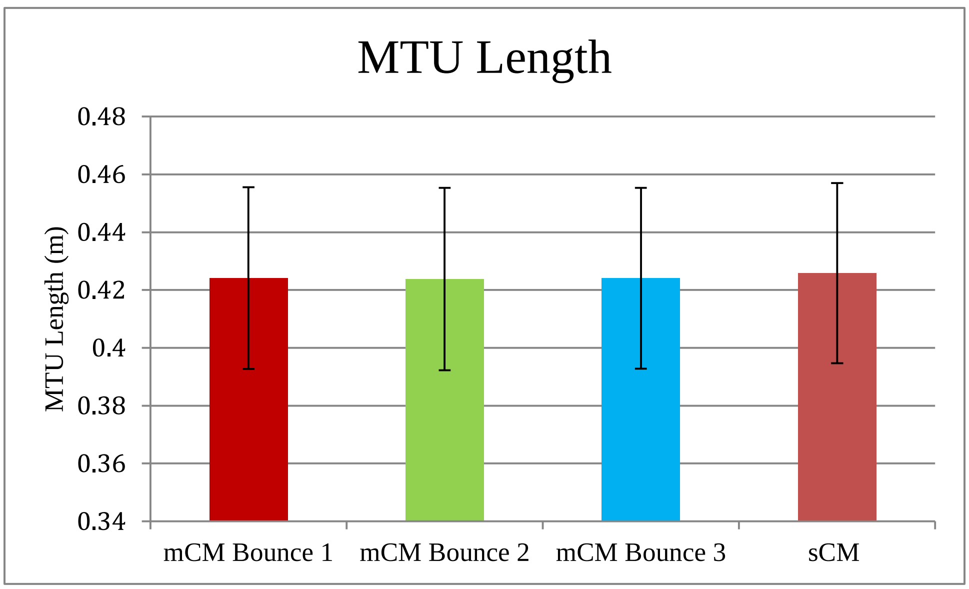

Figure 8- MTU length between CMs

Table 5- MTU length means

	MTU Length
Bounce 1	0.424 ± 0.0314m
Bounce 2	0.423 ± 0.0314m
Bounce 3	0.423 ± 0.0313m
sCM	0.425 ± 0.0312m

No significant difference was observed in MTU length for all conditions ($p = 0.087$). It can therefore be concluded that MTU length was not responsible for the higher MTU:CC ratio observed between the final bounce in mCM and sCM. CC length, however, was significantly shorter across multiple bounces and between Bounce 3 and the sCM. The significant difference in MTU:CC ratio in mCM and sCM can be attributed to significantly shorter CC length at the bottom of the final CM. This increased the contribution of tendon to total MTU lengthening resulting in higher elastic storage. Decreased CC length and higher elastic storage is likely responsible for the augmented performance in the mCM. The shorter fascicle length may have also allowed the muscle to operate at a more optimal force producing length. Furthermore, CC length was significantly different across the multiple bounces. This demonstrates that the CC length got progressively shorter with successive bounces. Bounce 1 was significantly shorter than Bounce 2, and Bounce 2 was significantly shorter than Bounce 3. No change in MTU length was observed between successive bounces so the shorter CC length contributed to enhancing elastic storage in the tendon while performing at their natural oscillation frequency.

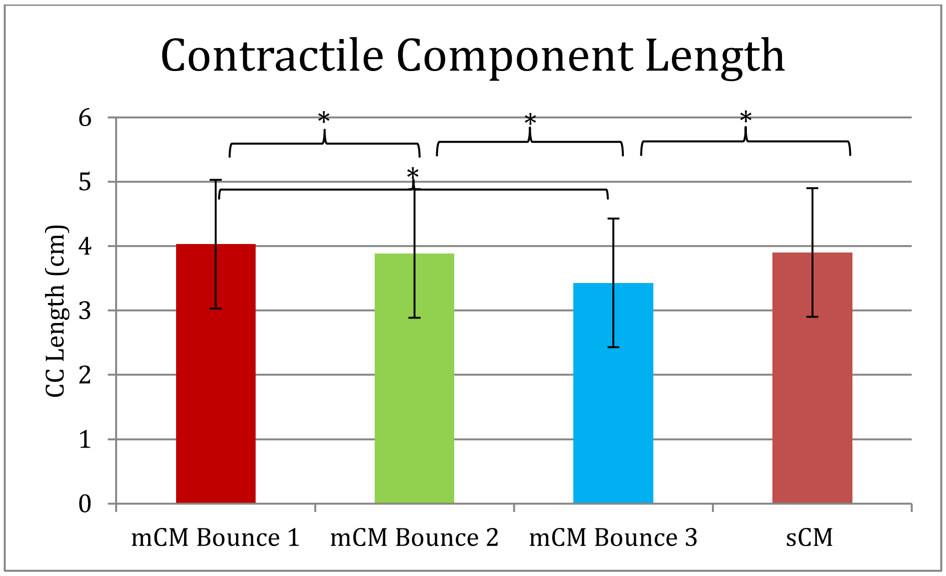

Figure 9 - CC length at each CM

Table 6- *$*p$ value ≤ 0.05*

	CC Length	**Bounce 1**	**Bounce 2**	**Bounce 3**	**sCM**
Bounce 1	4.02 ± 1.06cm		0.009*	0.000*	0.267
Bounce 2	3.88 ± 0.99cm	0.009*		0.001*	0.861
Bounce 3	3.42 ± 0.9cm	0.000*	0.001*		0.003*
sCM	3.9 ± 1.09cm	0.267	0.861	0.003*	

Discussion

The current study arrived at four main conclusions: (1) we were unable to determine resonance frequency by the MTU:CC ratio alone with the eight subjects we tested; (2) maximal SSC performance is related to performance at natural oscillation frequency; (3) subjects performed maximal height hop when performing mCM; and (4) performance augmentation in mCM can be attributed to enhanced elastic storage in tendon resulting from a shorter operating CC.

Resonance and Natural Frequency

We did not find that subjects performed maximal hops in either condition at their resonance frequency. Our results demonstrate that the MTU:CC ratio alone cannot determine the frequency at which resonance occurs. Other studies have shown resonance to occur at 3.07Hz (Dean & Kuo, 2011) and 3Hz (Takeshita et al., 2006). However, Dean and Kuo (2011) measured resonance to be the frequency at which energetic cost was minimized. Takeshita et. al (2006), calculated resonance to be the optimized MTU:CC ratio, however, they also calculated the work ratio, defined as the work produced by the fascicles over the work done by the MTU (Fascicle/MTU). At 3Hz, there was no significant difference in the work ratio between 2-3.67Hz. Furthermore, they reported no significant difference in MTU:CC ratio between their reported resonance at 3Hz and the amplitude ratio ratios at other frequencies. They too were unable to find a statistically different MTU:CC ratio to determine resonance frequency using similar methods to our study. Using the free-oscillation method to determine resonance/natural frequency could be a more accurate and reliable method than using the MTU:CC ratio alone.

It has been proposed that resonance frequency is related to the natural oscillation frequency of a system. Subjects performed their maximal mCM at their natural frequency. Subjects did not, however, bounce at their natural frequency in the sCM condition. This could be responsible for the higher MTU:CC ratio and performance observed in mCM compared to sCM. The current study found that maximal SSC performance is frequency dependent. We observed a strong negative correlation ($r = -0.6$, $p = 0.018$) in both conditions between hop height and the difference between natural frequency and CM frequency. The results demonstrate that as subjects perform the CM closer to their natural frequency, hop height increases. To the best of our knowledge, this is the first study to show that maximal SSC performance is dependent on performing at natural frequency.

Hop Height

Hop height was significantly higher in the mCM compared to the sCM condition. Because we found no significant correlation between MVIP and either hop condition, maximal isometric strength of the plantarflexors may not be the underlying mechanism for maximal performance in a hopping task. Augmented performance in the mCM compared to sCM is likely the result of a maximized MTU:CC ratio and elastic storage by making use of mechanical resonance in the tendon. Furthermore, we found that performance is related to how close subjects performed to their natural frequency. This could have enhanced the resonant properties of the MTU and storage of elastic energy in the tendon. This would explain the difference in performance between the conditions. Van Werkhoven and Piazza (2013), found that subjects and a computer model hopped highest when utilizing a mCM strategy. Maximal hop heights reported by van Werkhoven and Piazza (2013), (18.7 ± 4.5cm) were higher than the hop heights found in the current study. Van Werkhoven and Piazza (2013) calculated hop heights from the difference in height of a sacrum marker between its peak and reference standing position. The difference in calculation of hop height could be responsible for the different results. They proposed increased tendon energy storage as the most likely mechanism for increased performance in human subjects and simulation. The mean frequencies of the final bounce in bouncers and computer model were 2.78 and 2.53Hz respectively. These frequencies were close to the resonant frequencies found in other studies. Their subjects, who did not jump highest using a mCM strategy, performed their final bounce at 1.46Hz. This is a frequency much lower than the resonance frequencies found in the current study and others. At resonant frequency, muscle fiber excursions are minimal compared to the length changes of the entire muscle-tendon unit. This quasi-isometric behavior of the muscle at resonance will enhance storage of elastic energy in the tendon. If the CM is not performed at natural frequency, resonance may not occur, resulting in lower elastic storage. In the current study, it was found that the MTU:CC ratio was significantly higher in the final bounce in mCM than the sCM. Performance was augmented in mCM for all subjects except four. This group was termed the non-augmented group (n=4). A paired samples t-test was performed on the amplitude ratio between the final bounce in mCM and sCM. For these four subjects, there was no significant difference between the MTU:CC ratios in both conditions ($p = 0.682$). These four subjects may not have been able to optimize elastic storage in the tendon using mCMs. Furthermore, no significant differences between CC length and MTU length were found between the two conditions ($p = 0.713$ and $p = 0.588$, respectively). Since these variables did not change between conditions, elastic storage could perhaps not be increased using multiple bounces for these four subjects. For the non-augmented group, MTU:CC ratio alone did not have a linear relationship with hop height or differences in hop height between conditions; however, it can explain the differences observed between the mCM and sCM jump within subjects. Performance of CM close to natural frequency can better explain the differences observed in hop height between subjects than can the MTU:CC ratio. Difference between MTU:CC ratio, CC lengths, and MTU lengths will be analyzed in the following section.

Muscle-Tendon Behavior

We found that subjects had a significantly higher MTU:CC ratio between the final CM in mCM and sCM. The significantly higher ratio indicates greater elastic storage in the tendon prior to the push-off phase of the maximal height hop. The higher MTU:CC ratio observed in mCM compared with sCM, and performing the CM at the natural oscillation frequency, could be linked to mechanical resonance and optimized storage of elastic energy in the tendon. Enhanced elastic storage could then be attributed to the augmented performance in mCM. CC length and MTU length were compared across bounces and conditions in order to determine which of the variables was most responsible for the higher ratio in the final bounce of mCM and sCM. It was found that MTU length was not responsible for the higher ratio with no significance between all CMs. We determined that significant changes in CC length were responsible for the amplitude ratio difference between mCM and sCM. As the subjects performed repeated bounces the CC length shortened as well increasing the contribution of tendon to total MTU lengthening with each successive bounce. Since we defined resonance as maximized MTU:CC ratio we can conclude that subjects performed the mCM closer to resonance than in the sCM. The enhanced elastic storage due to mechanical resonance is likely responsible for the higher performance in mCM compared with sCM.

Conclusion

In conclusion, the current study found that resonance could not be determined using the frequency at which highest MTU:CC ratio occurs as the definition for resonance frequency. Furthermore, each subject's natural oscillation frequency may be a better indicator of resonance frequency. We found that maximal SSC exercise is dependent on how close to natural frequency it is performed. Subjects performed the mCM at their natural frequency and optimized elastic storage by maximizing their MTU:CC amplitude ratio. Enhanced elastic storage is primarily due to fascicle shortening with successive bounces resulting in higher strain applied to the tendon. These conditions are likely responsible for the higher hop performance in mCM compared to the sCM condition.

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Vita

Daniel Lidstone was born in Vancouver, Canada. After graduating from St. Michaels College School in Toronto, Daniel attended Wilfrid Laurier University and graduated with a BA in Honors Kinesiology & Physical Education. After graduating, Daniel went on to pursue his Masters of Science Degree from Appalachian State University and graduated in May 2015. Daniel plans to pursue a Ph.D. in Exercise Science with a focus on stretch-shortening cycle function. Daniel’s parents, Darrel and Roseanne Lidstone, and brother Kellen Lidstone reside in Canada.