Lower Leg Characteristics Influance on Hopping Height

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Abstract: It has been suggested that certain lower leg variables affects running and jumping performance. However, it is unclear how these variables interact with each other, and how they jointly affect hopping performance. We assume that AT-MA influences the physical performance differently depending upon biomechanical variables of the plantar flexor muscles. We hypothesize that no single variable can explain hopping height, rather a combination of lower leg variables can explain the variation in hopping height. Healthy young adults (n = 28, age 21.8 ±4.0 yrs) performed serial hops on a force plate during which we recorded right leg joint kinematics, lateral gastrocnemius fascicle behavior, and plantar flexor electromyography activity. We found no correlation between hopping height and AT-MA (r=0.28, p=0.14). Multiple regression analyses revealed that variations in AT-MA, ankle dorsiflexion amplitude, and peak ground reaction force explained 53% of the variation in hopping height. We concluded that even a combination of selected biomechanical variables can only moderately account for hopping performance.

Keywords: Human ankle; moment arm; EMG; vertical jump

1 Introduction

Biomechanical properties of the plantar flexors (i.e. ankle joint range of motion, muscle electrical activity, fascicle, and tendon behavior) and the structure of the ankle joint (i.e. moment arm length), are key determinants of vertical hopping performance. Because the product of muscle force and moment arm length is muscle moment, it is reasonable to expect that individuals with longer AT-MA would generate higher plantar flexors moments with lower and faster force generation hence greater efficiency. Against such expectations, experimental data seem to suggest that sprint performance (Kumagai et al., 2000; Lee and Piazza, 2009; Baxter et al., 2012) and running economy are associated with shorter instead of longer AT-MA [1, 36, 41].

Achilles tendon moment arm length (AT-MA) can increase or decrease the magnitude of ankle joint power in various types of joint movement [3, 37, 45, 46].

Because of these contradictory results it remains uncertain how the AT-MA length affecting joint output. We can assume that different types of joint movements might benefit from a long AT-MA while other types of movements benefit from a short one. Also, it is reasonable to assume that other important variables which are also influence joint output (i.e. muscle strength, neuromuscular activation pattern (force generation capacity), joint range of motion (ROM), fascicle, and tendon behavior) affected by the AT-MA length.

Two-legged hopping mainly uses ankle thrust which makes it an ideal task to experimentally examine the effects of the ankle joint properties (AT-MA, fascicle length, plantar flexor length changes, muscle activation) on motor performance under dynamic condition. Repetitive vertical hopping has been extensively studied [4, 6, 9, 10, 15, 16, 25, 42], but only a few studies have focused on the effects of AT-MA length on hopping performance [44, 45]. Volleyball players and runners have shorter moment arm than controls and while volleyball players jump the highest, such differences in jumping performance were independent of AT-MA length but other ankle properties were not examined [44]. In contrast, there was a strong correlation of r = 0.74 between heel length, a proxy measure of AT-MA length, and maximal jump height, a measure of mechanical power [45]. However, it should be noted that in this study the vertical jump was carried out with plantar flexion only (static jump), i.e., the plantar flexors contracted concentrically, which can explain the benefit of a longer moment arm based on the force-velocity-power relationship [18].

The magnitude of plantar flexor force and ankle ROM can affect hopping height [29, 30]. While longer AT-MA length can produce greater muscle moments [46], individuals with a short AT-MA length can rotate the ankle through a greater ROM and jump higher [41, 44]. The larger ROM is also associated with greater negative and positive accelerations of the center of mass during hopping and thus increase jump height [29, 45]. Thus, greater ankle ROM lengthens the muscle-tendon unit more, producing greater shortening velocities, positive work, and ultimately jump height. Indeed, athletes with greater jump height operated muscle fascicle close to resting length, which increased tendon lengthening during joint flexion [40]. The longer tendon stretch increases the amount of the stored elastic energy, which can be reused in the subsequent joint extension [33]. When fascicles operate in a quasi-isometric state, the greater tendon lengthening requires a greater muscle tensile force, resulting in an increase in muscle activation. In particular, during a powerful and fast stretch of the MTU, such as during hopping, the short-latency stretch reflex can become active [28]. Such a cascade of events, i.e., increased muscle activation and muscle force generation underlies higher jumps.

The purpose of the study was to investigate what/which set of variables could predict the most accurately hopping height. In addition to previous studies, we aimed to investigate also the relation between AT-MA and 1) ankle joint ROM, 2) plantar flexor electromyography activity, 3) LG fascicle behavior and 4) Force-related variables derived from a force platform. We hypothesized that longer AT-MA would associate with lower plantar flexor electromyography activity, greater maximal vertical ground reaction force, and force development ratio. In addition, we do not expect that AT-MA correlates with hopping height, rather than correlate with the aforementioned variables which contribute to achieving superior hopping height.

2 Methods

2.1 Participants

Healthy young adult volunteers participated in the study (n=28, age 21.8 ±4.0 yrs, height 1.80 ±0.8 m, body mass 80.2 ±6.1 kg). They were free of pain and had no injuries to the lower extremities over the past two years. Participants gave written informed consent prior to the start of the study, which was performed in accordance with the Declaration of Helsinki and was approved by the local ethics (TE-KEB/No5/04/2017).

2.2 Experimental Protocol

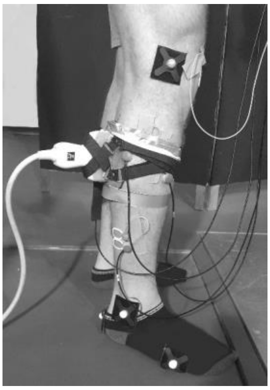

Figure 1

Installation and fixation of US probe, EMG electrodes on the right shank, and location of the markers on the foot, ankle and knee joint

After participants received a detailed explanation of the protocol, they warmed up by cycling on an ergometer for 10 minutes. Surface EMG electrodes and an ultrasound probe were attached to the lower leg. After several minutes of practice of repetitive two-legged hopping, participants stood barefoot on a force platform with arms akimbo and were asked to hop 10-12 times with gradually increasing effort to reach maximal hopping height. Participants were instructed to keep their knee and hip joints as straight as possible while hopping. Knee and ankle joint angular displacement, ground reaction force (GRF), electrical activity (EMG) of ankle plantar flexor muscles, and fascicle behavior of the lateral gastrocnemius were recorded during the hops (Fig. 1). AT-MA was estimated. All measurements were carried out on the dominant (right) lower extremity.

2.3 Kinetic and Kinematic Data Collection and Analyses

Participants performed hopping on a force plate (Kistler Force Platform System 92-81B, Switzerland, sampling rate 1 kHz) while being videotaped at 120 Hz by a digital camera set at 1m height on a tripod, four meters from the force platform perpendicular to the sagittal plane of the participant. To measure ankle and knee ROM, four retroreflective markers (1.5 cm diameter) were placed on the skin on the right leg on the: greater trochanter of the hip; lateral condyle of the tibia, and lateral malleolus of the ankle, and on the 5th metatarsal head of the foot. Video images were digitized in 2D (Skillspector software, v. 1.2.4, Denmark). From the force-time curve, contact and flight times, and the peak GRF were determined. Rebound height was calculated from the flight time [40]. The reactive strength index was computed as the ratio of the flight and contact times [13] to select the best three hops. Data of these three hops were time normalized and averaged. The braking and take-off phase and their duration was determined from the ankle angular displacement-time curve. The anatomical angle of the knee joint is zero when the longitudinal axis of the thigh and shank is aligned. However, we used the other angle determination, where this angular position represents 180 degrees. In terms of the ankle joint, the angle of the joint was considered zero when the shank was perpendicular to the foot base (sole). Ankle ROM was calculated from the angular displacement-time curve. The peak GRF was normalized to body weight (rGRF).

2.4 EMG Data Collection and Analyses

EMG signals were recorded during hopping at a sampling frequency of 1 kHz (TeleMyo, Noraxon U.S. Inc., Scottsdale, Az, USA). After skin preparation, silver-silver chloride bipolar surface electrodes (Blue Sensor M-00-S/25, Ambu, Denmark) with a 10 mm diameter and an inter-electrode distance of 20 mm (center-to-center) were placed on the medial gastrocnemius (MG), lateral gastrocnemius (LG), and soleus (SOL). For LG and SOL, the electrode placements were defined using ultrasonography. The electrodes were placed on the lateral side of the SOL to minimize cross-talk between SOL and adjacent muscles [38]. For LG, EMG electrodes were placed slightly lateral to the muscle midbelly so that the ultrasound probe could be placed correctly (ultrasound preparation detailed below). For MG, the electrodes were aligned parallel with the fascicle orientation and were placed according to SENIAM guidelines [17]. The reference electrode was placed on the ipsilateral patella. To minimize movement artefacts, EMG cables were taped over the skin.

The EMG signals were band-pass filtered (20-450 Hz) with a 4th order zero-lag Butterworth filter to remove movement artefacts and signal noise. Root-mean-square values (RMS) were calculated the pre-activation, eccentric, and concentric phases of each hop. The RMS envelopes were integrated for each phase and divided by the integration time to calculate the average EMG activity [12].

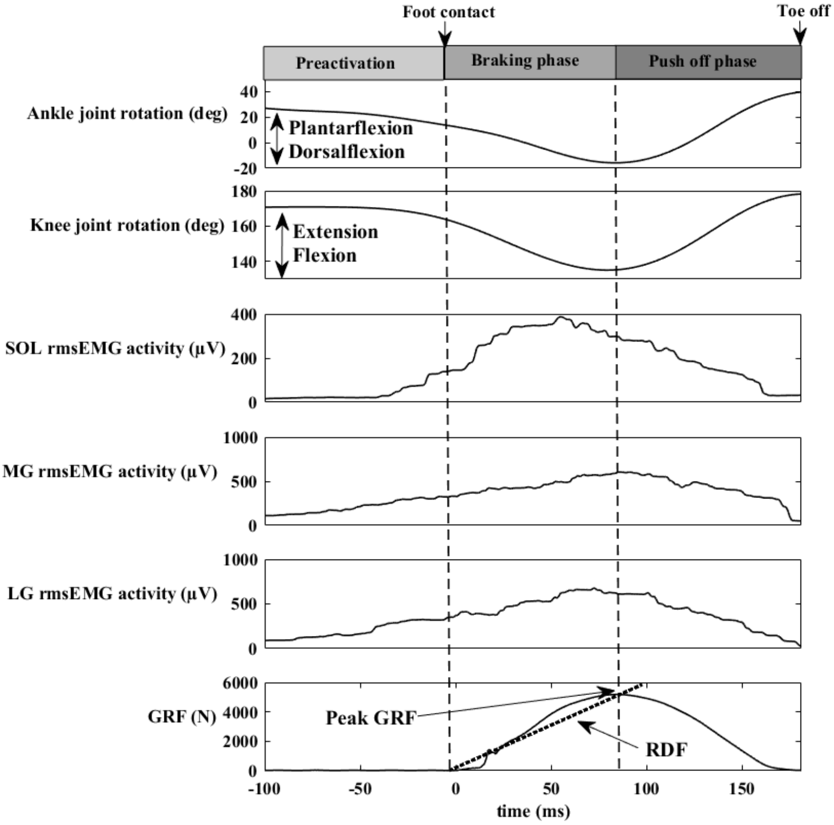

Figure 2

Ankle angular displacement, electric activity (EMG) for gastrocnemius medialis (MG) and lateralis (LG), soleus (SOL) muscles, and the vertical ground reaction force (GRF) curves in the function of time in the case of one participant. The first area refers to the preactivation time (100 ms). The second and third area represents the braking and take-off phase duration during the ground contact pGRF represents the peak ground reaction force and RFD is the rate of force development, i.e., pGRF divided by the time from zero to pGRF. Neutral knee joint angle was considered 180° between shank and thigh and neutral ankle joint angles was considered 90° between foot and shank.

Pre-activation was the 100-ms period before foot contact [26]. EMG ratios were calculated by dividing average EMG in the stretching phase by average EMG in the pre-activation phase, and average EMG in the shortening and stretching phases [21]. The EMG records were synchronized with the kinematic records and phases were determined from the joint angle data. (Fig. 2.)

2.5 Ultrasonography Data Collection and Analyses

Ultrasonography was used to estimate architecture and architectural changes in LG during hopping (50 frames·per sec^{-1}, 6 cm field-of-view, B-mode linear array probe, 7.5 MHz scanning frequency, Hitachi-Aloka EUB 405 plus, Japan). The ultrasound probe was placed over the right LG in the plane of the fascicles and was secured using a custom-made cast and tightly fixed around the shank to minimize probe movement relative to the skin (see in supplementary material). A custom-made synchronization module was used to synchronize the kinematic, kinetic, EMG, and ultrasonography recordings. LG fascicles were manually outlined and fascicle length measured (Fig. 3). Multiple contour lines were fitted to follow fascicle curvature. If part of the fascicles was outside the field-of-view, fascicle length was estimated by linear extrapolation. Images were processed in ImageJ (v.1.44b National Institutes of Health, USA).

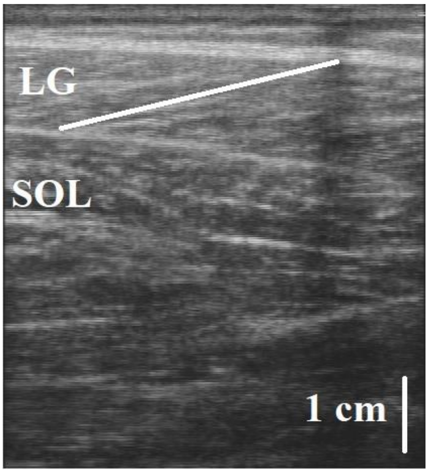

Figure 3

Representative ultrasound image of soleus in sagittal plane for estimate fascicle length. The image was taken at 50% of the muscle length because that region possibly contains the longest fascicles of the muscles. Fascicle length (solid white line along fascicles), are drawn in the images.

2.6 Estimation of AT-MA

We used a photograph-based method to estimate AT-MA length [41]. Briefly, the participants were seated with the right foot on a reference block and the ankle in a position. The foot was photographed from both the lateral and medial sides in the sagittal plane. The most prominent tip of the lateral and medial malleoli was marked on the skin and the horizontal distance from the markers to the posterior aspect of the Achilles tendon were measured on both sides [41] using ImageJ software (v. 1.8.0_112, USA 2006). The mean of these two distances was defined as the length of the AT-MA (Fig. 4).

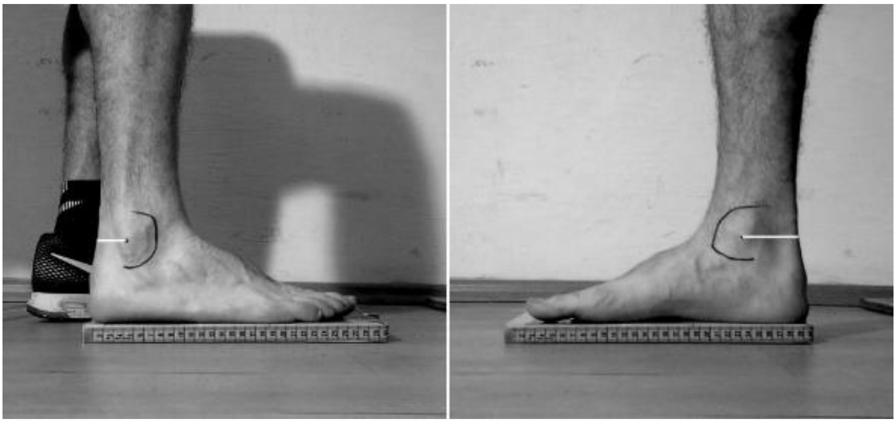

Figure 4
A typical sagittal photograph of the right ankle placed on and aligned with a reference block. The horizontal distance from the medial and lateral malleolus to the Achilles tendon was determined (white lines). Moment arm was calculated as the mean of these two distances

2.7 Statistical Analysis

Data are presented as mean and standard deviation (±SD). The distribution of the data was checked with the Shapiro–Wilk test. Relationship between variables was estimated with Pearson’s correlation coefficients (r), which was categorized as small (0.0-0.1), moderate (0.1-0.3), medium (0.3-0.5), large (0.5-0.7), and very large (0.9-1.0) [22]. Additionally, the 95% confidence intervals for each coefficient was calculated. In cases of non-Gaussian data distribution, a Spearman rank correlation was used. Multiple regression was used to determine the variables that predicted most accurately hopping height. The level of significance was set at $p \leq 0.05$.

3 Results

Tables 1-2 show descriptive data for all outcomes. Table 3 shows the correlation between the hopping height and the selected variables. Hopping height only correlated with knee ROM (extension amplitude) but not with ankle and plantar flexor variables, ankle joint kinematics, and EMG variables. There was a strong relationship between hopping height and force variables, i.e., peak ground reaction force (pGRF), normalized peak ground reaction force (pGRFr), and rate of force development (RFD) (Table 3).

Table 1

Hopping kinematics and ground reaction force (GRF), mean SD

Variables	mean ±SD
Hopping height (m)	0.24±0.06
Contact time (s)	0.186±0.02
Flight time (s)	0.435±0.05
Contact to flight time ratio	2.36±0.41
Braking phase duration – [Tcon] (s)	0.082±0.016
Push off phase duration – [Tecc] (s)	0.102±0.015
Ankle flexion amplitude (rad)	0.51±0.18
Ankle extension amplitude (rad)	0.83±0.19
Knee flexion amplitude (rad)	0.34±0.14
Knee extension amplitude (rad)	0.68±0.11
Peak GRF (N)	4498.7±995.2
Normalized peak GRF (N/kg)	65.72±8.26
Rate of force development (N/s)	58220±20302

Table 2

Achilles tendon moment arm length, gastrocnemius lateralis fascicle, and plantar flexor electromyography activity variables. EMG activity measured during ankle flexion (STR) and divided by EMG in preactivation (PRA) (STR to PRA) and EMG during ankle extension (SHO) divided by EMG in ankle joint flexion phase (SHO to STR). Muscles: soleus (SOL), medial gastrocnemius (MG), lateral gastrocnemius (LG)

Variables	mean ±SD
Achilles tendon moment arm (cm)	4.29±0.75
Normalized Achilles tendon moment arm (ratio)	16.16±2.56
Fascicle length	4.24±0.85
Fascicle length change during joint flexion (cm)	0.03±0.54
Fascicle length during joint extension (cm)	-0.38±0.47
STR to PRA SOL	4.67±3.38
STR to PRA MG	2.66±1.62
STR to PRA LG	1.76± 0.5

SHO to STR SOL	0.87±0.44
SHO to STR MG	0.90±0.34
SHO to STR LG	0.83±0.28

Table 3
Correlation between hopping height and variables of plantar flexor, Achilles tendon, joint kinematics, ground reaction, and EMG activity. Asterisks indicate a significant correlation

Hopping height		Independent variable	AT-MA length	
r	p value		r	p value
0.28	0.14	Achilles tendon moment arm	-	-
0.23	0.23	Resting fascicle length	0.06	0.74
-0.09	0.65	Fascicle length change (flexion)	0.18	0.35
0.14	0.47	Ankle flexion amplitude	-0.48	0.009*
0.25	0.19	Ankle extension amplitude	-0.39	0.037*
0.18	0.25	Knee flexion amplitude	-0.41	0.03*
0.53	0.001*	Knee extension amplitude	-0.20	0.31
0.08	0.66	EMG STR to PRA ratio SOL	-0.17	0.32
-0.14	0.47	EMG STR to PRA ratio MG	-0.2	0.31
0.23	0.23	EMG STR to PRA ratio LG	-0.08	0.88
-0.16	0.41	EMG SHO to STR ratio SOL	-0.02	0.99
-0.15	0.42	EMG SHO to STR ratio MG	-0.03	0.98
-0.19	0.32	EMG SHO to STR ratio LG	-0.06	0.92
0.69	0.001*	Peak ground reaction force	0.64	0.001*
0.48	0.008*	Normalized ground reaction force	0.63	0.001*
0.57	0.001*	Rate of force development	0.48	0.001*

*significant correlation

Additional correlations

Ankle dorsiflexion and plantar flexion amplitude correlated with joint flexion (Tecc) and extension (Tcc) time, respectively ($r=0.64$ $p<0.001$ and $r=0.67$ $p<0.001$). Knee flexion and extension time and amplitude were also interrelated ($r=0.61$ $p< 0.001$and $r= 0.76$ $p<0.001$). There was an inverse relationship between rGRF and ankle dorsiflexion amplitude ($r=-0.43$ $p<0.01$) and between RFD and ankle dorsiflexion ($r=-0.56$, $p=0.01$).

Summarizing the correlations AT-MA did not correlate with hopping height ($r=-0.28$, $p<0.14$), but it was related to peak GRF and RFD so that both force-related variables correlated with hopping height. AT-MA, negatively correlated with joint kinematic variables (ankle and knee flexion amplitude) which correlated also negatively with peak GRF and rate of force development. Concentric contraction duration did not correlate with GRF and RFD. Only knee extension amplitude correlated with hopping height (Fig. 5).

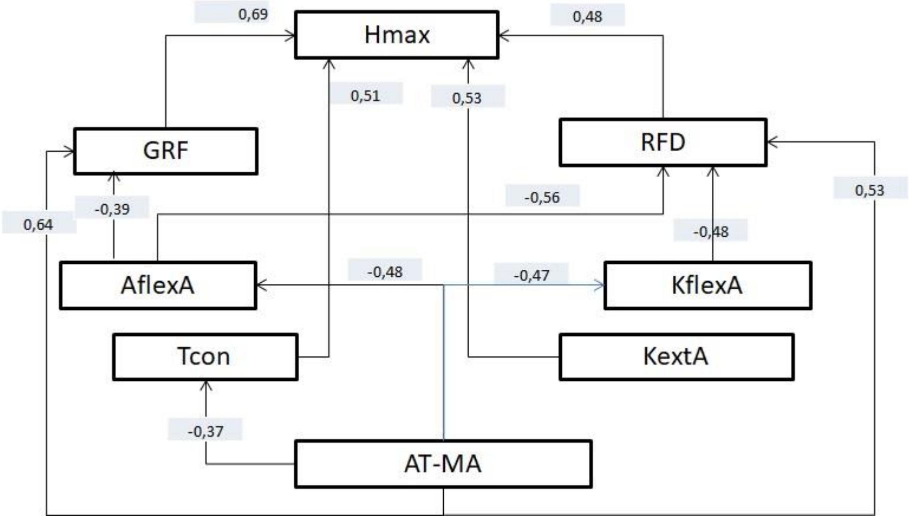

Figure 5
Correlation between dependent and independent variables. Numbers shows the correlation coefficients between the variables. Abbreviations: Hmax – maximal hopping height, GRF – ground reaction force, RFD – rate of force development, AflexA – ankle flexion amplitude, KflexA – knee flexion amplitude, Tcon - concentric contraction time, KextA – knee extension amplitude, AT-MA – Achilles tendon moment arm length

In a multiple linear regression analysis, AT-MA length, ankle dorsiflexion amplitude, and peak GRF explained 53% of the variation in hopping height (F (3,24) =5.85, p=0.001. R^2 = 0.53). The model met the assumptions of the multiple regression model described by Field [11]. The Durbin-Watson statistic (2.23) revealed no autocorrelation in the residuals. The tolerance and VIF values also showed that there is no multicollinearity between the variables (see in supplementary materials).

4 Discussion

The purpose of the study was to determine the relationship between AT-MA, joint kinematics, ground reaction forces, plantar flexor electromyography activation, lateral gastrocnemius fascicle behavior, and hopping height.

The hypothesis was that no single variable is related sufficiently strongly to hopping height rather a certain combination of variables predicts hopping height.

Over the past 20 years, a number of studies has sought to determine the relationship between AT-MA or calcaneus length and sprint and distance running performance. We thought that repetitive hopping is ideal to study the effect of the selected ankle characteristics on hopping height because it results in a real stretch-shorten muscle contraction of the plantar flexor muscles in which mostly Achilles tendon carry out both negative and positive mechanical work. On the other hand, continuous rebound jump provides the greatest muscle stretch versus other jumps (i.e. countermovement jump, squat jump, static jump).

Interestingly, there have been relatively few studies, in which hopping was used to test the connection among these variables [44, 45]. The hopping protocol in our experiment was similar to that of Watanabe et al. [44]. Namely, we used repetitive vertical bilateral hopping.

Watanabe et al. [44] did not find a correlation between the AT-MA and hopping height or with other muscle-tendon complex variables. Werkhoven and Piazza [45] found that subjects having longer heel length (indicate a longer AT-MA) were able to jump higher using a single static jump restricting knee and hip joint rotation. In this case, the relationship can be explained, because only plantar flexor muscles force is used to accelerate the body mass. To produce the same moment less muscle force is needed when the lever arm is longer and the same muscle should exert less force it can shorten faster. However, repetitive vertical hopping differs very much from single static hop. Namely, during static hop, the plantar flexor muscles produce force by muscle shortening, while in repetitive hopping the muscle is stretched during the ankle dorsiflexion resulting in enhanced motor unit activation and elastic energy storage in the Achilles tendon [4, 6]. The question arises whether the long AT-MA is also beneficial during muscle stretch? Theoretically, short-moment arm can be advantageous because the muscle should exert greater force, and therefore the tendon stretch, ergo elastic energy storage can be greater. It is well documented in the literature that during SSC movement the fascicles operate under isometric contraction and therefore the tendon is stretched mostly during joint flexion [23, 24, 27, 32]. In our study, we could not measure the Achilles length change, but the short, not significant length change of the fascicle length in lateral gastrocnemius may indicate that the Achilles tendon was stretched predominantly. However, it should be noted the inter-individual variation in fascicle length change was very high that may indicate fascicle behavior adaptation to joint kinematics and AT-MA length.

Although the AT-MA length changes in a function of joint angle and force exerted by the muscle [14, 43], it cannot be assumed that the Achilles tendon length changes could be shorter during dorsiflexion and longer during joint plantar flexion to meet the quality criteria in both contraction type. Nagano and Komura [37] in a model design suggested that AT-MA length and also contraction speed influence the mechanical moment and mechanical power differently during eccentric and concentric contraction. In contrast to the results of Wekhoven and Piazza [45] they found that a shorter moment arm increases ankle joint moment during concentric contraction.

During hopping when joint flexion and extension occurs the muscle undergoes a stretch shorten type of contraction, it is not clear either a long or a short AT-MA would be beneficial. We think that can be because other important factors have also influenced the joint output as well, thus a different combination of these variables can explain more accurately the joint performance. We thought that subjects may use different joint kinematic strategies depending upon the AT-MA length to jump as high as possible. Therefore, we assumed that there might be no correlation between AT-MA and hopping height. Indeed, in this experiment, we did not find an association between AT-MA length and hopping height, but the strong correlation was between AT-MA and ankle and knee flexion amplitude, i.e. the greater the AT-MA length the smaller was the joint flexion. This could lead a greater deceleration at the end of the joint flexion and therefore the peak GRF and RFD became greater. This assumption is supported by the strong correlation between peak joint flexion amplitude and GRF and RFD, i.e. the shorter the joint flexion the greater was the peak GRF and RFD, and as a consequence the greater the peak force and RFD the highest was the hopping height. These relationships were supported by the multiple regression analysis because the three independent variables (MA-TA, ankle dorsiflexion amplitude, and peak GRF) jointly influenced the hopping height. In addition, AT-MA showed a strong correlation with both peak GRF and RFD indicating that longer AT-MA is beneficial for muscles to exert a greater force on the ground and develop force within a shorter time.

It could be assumed that if the ankle and knee joint angular deceleration was increased then plantar flexor muscles should generate greater force and therefore muscle activation is enhanced indicated by EMG activity, i.e. in our case greater stretch to pre-activation EMG ratio. Sano et al. [40] in a similar study reported that Kenyan runners jumped higher than the control group with a greater stretch to pre-activation EMG ratio during hopping.

We could not detect a correlation between EMG ratios and other variables that is hard to be explained. However, we have to stress that the EMG ratio that we used may not be the best indicator of muscle activation level, since we found a significant correlation between pre-activation EMG and stretching EMG. Namely, when the pre-activation EMG increased the stretching EMG also increased. So that, we can speculate that soleus and gastrocnemius muscle had neuromuscular potentiation due to the muscle stretch because there was a correlation between RFD and ankle dorsiflexion amplitude and as a consequence, the greater hopping height was associated with greater RFD and smaller ankle dorsiflexion amplitude.

So that, we can speculate that soleus and gastrocnemius muscle had neuromuscular potentiation due to the muscle stretch because there was a correlation between RFD and ankle dorsiflexion amplitude and as a consequence, the greater hopping height was associated with greater RFD and smaller dorsiflexion amplitude.

From the results of the correlation analysis and the related measured variables (i.e. small change in fascicle length), we can assume that the shorter ankle dorsiflexion amplitude and longer AT-MA made the elastic energy storage and reuse possible in the Achilles tendon, which is very important in enhancing jumping height [4, 6, 10, 15].

Comparing our results with those of others concerning the achieved hopping height in our study is heavily relies on a well-coordinated joint movement [5, 7, 8, 35], and our measured ankle and knee joint ROM were similar to previous reports [19, 40, 44]. The measured hopping heights performed by our participants are also similar to those reported in earlier studies [19, 20, 40] thus we can conclude that participants in this study performed the hopping similarly. However, we have noted that the variables involved in our study may have different associations if the knee and hip joints were fixed. In this respect we have to mention that knee extension amplitude, in the present study, had a direct and independent correlation with hopping height that probably modified the effect of ankle-related variable.

This experiment has some methodological limitations that should be addressed. To estimate the AT-MA length we used a low-tech method similar to previous reports [41, 45, 47]. The measured lengths were similar to those in previous reports and not differ remarkably from MRI-based estimations [39]. However, the AT-MA length is changing constantly with joint rotation [14, 43], therefore, it can influence the results of our report. Furthermore, the investigation of tendon characteristics and length changes during the hops could provide more information about the efficiency of the elastic strain energy store and reuse mechanism. To study the length changes of LG, a two-dimensional ultrasound technique was used despite the three-dimensional structures of this muscle. This method has potential errors that occur during hopping and other dynamic movement and it is not possible currently to quantify the amount of error and may not be consistent throughout the hop cycle. The mean fascicle length changes are in accordance with previous results. However, there is a large inter-individual variance in these data which must be considered. The ankle plantar flexor muscle strength and muscle morphology (volume, mass) were not assessed in this study, and these parameters obviously determine the hopping performance. Thus, it would be ideal to include these variables in future studies.

Conclusions

Our results suggest that AT-MA length does not affect the flying height when hopping is carried out with stretch-shorten cycle contraction, using repetitive double-legged hopping. However, we may conclude that AT-MA has an indirect association with hopping height via maximum force generation, force development, and pushing off phase time. Also, our results indicate that AT-MA length can influence hopping height jointly with the electromyography activity of plantar flexor muscles (gastrocnemius medialis in our case), maximum force generation, and rate of force development.

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