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Kinetics and activity of the lower extremity muscles to achieve a higher height during repeated vertical jumps

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Kinetics and activity of the lower extremity muscles to achieve greater height during repeated vertical jump performance
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ABSTRACT. *Objective.* To determine the key factors of the kinetic and muscular activity of the lower extremities to improve the technique and height during repeated vertical jumps.
Methods. Eighteen athletes (age 20.7 ± 0.9 years, height 1.79 ± 0.05 m, body weight 83.2 ± 15.2 kg) performed five maximum vertical jumps on the power platform. Kinematic characteristics in the sagittal plane were measured using a high-speed video camera. The strength of the support reaction and electromyography (EMG) of the muscles of the lower extremities were recorded simultaneously.
Results. The average height of the jump was 0.34 ± 0.08 m, which positively correlated with the positive mechanical work of the ankle joint (r = 0.73, p <0.001) and knee joints (r = 0.60, p <0 , 01). Rotational impulse of the knee joint during the extension phase (r = 0.61, p <0.01), the maximum angle of backward inclination of the femoral segment (r = 0.72, p <0.001), EMG of the gluteus maximus , 60, p <0,01) and rectus femoris (r = 0,54, p <0,05) also positively correlated with jump height.
Conclusions. These data show that the knee joint plays an important role in achieving greater jump height. The large gluteal muscle generates greater torque to straighten the knee joint and significant positive mechanical work to rotate the thigh forward, thereby accelerating the body vertically and ensuring a greater jump height.
Keywords: jump, kinetic characteristics, stretching-contraction cycle, torque, EMG.

Кінетика і активність м’язів нижніх кінцівок для досягнення більшої висоти стрибка вгору при багаторазовому повторенні
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АНОТАЦІЯ. *Мета.* З’ясувати ключові фактори кінетичної і м’язової активності нижніх кінцівок для покращення техніки і висоти стрибка в гору при повторних вертикальних стрибках.
Методи. Вісімнадцять легкоатлетів (вік 20,7 ± 0,9 року, зріст 1,79 ± 0,05 м, маса тіла 83,2 ± 15,2 кг) виконували п’ять максимальних вертикальних стрибків на силовій платформі. Кінематичні характеристики у сагітальній площині вимірювались за допомогою високошвидкісної відеокамери. Силу реакції опори і електроміографію (ЕМГ) м’язів нижніх кінцівок реєстрували одночасно.
Результати. Середня висота стрибка становила 0,34 ± 0,08 м, що позитивно корелювало з позитивною механічною роботою надп’ятково-гомілкового суглоба (r = 0,73, p < 0,001) і колінних суглобів (r = 0,60, p < 0,01). Обертальний імпульс колінного суглоба під час фази розгинання (r = 0,61, p < 0,01), максимальний кут нахилу назад стегнового сегмента (r = 0,72, p < 0,001), ЕМГ великого сідничного м’яза (r = 0,60, p < 0,01) і прямого м’яза стегна (r = 0,54, p < 0,05) також позитивно корелювали з висотою стрибка.
Висновки. Ці дані показують, що колінний суглоб грає важливу роль у досягненні більшої висоти стрибка. Великий сідничний м’яз генерує більший обертальний момент випрямлення колінного суглоба і значну позитивну механічну роботу для обертання стегна вперед, тим самим вертикально прискорюючи тіло і забезпечуючи досягнення більшої висоти стрибка.
Ключові слова: стрибок, кінетичні характеристики, цикл розтягування-скорочення, обертальний момент, ЕМГ.

Introduction

Repeated vertical jump (RVJ) is a useful tool for several purposes in sports. It is well known that this exercise is used as a part of plyometric training which is exercises to enable a muscle to reach its maximum power in the shortest possible time [7]. The drop jump (DJ) is a very similar movement, but RVJ is easier for untrained individuals to perform and does not require any apparatus [16]. Furthermore, it is easier to anticipate landing in RVJ than DJ, which Zushi and Takamatsu [21] have suggested is an important factor in DJ performance.

RVJ can be used as an evaluation exercise as well as a training method. Zushi, et al. [22] proposed a DJ-index and/or rebound jump (i.e.,., RVJ) index (RJ-index), which is the jumping height divided by contact time. Furthermore, they reported a significant correlation between this index and the power of the lower limb muscles. Iwatake, et al. [10] reported a significant relationship between RJ-index and sprint performance. Zushi, et al. [20] also reported that the jumping height of RVJ correlated positively with jumping performance in track-and-field events. It is suggested that jumping performance can be estimated by RVJ, which has been widely used as not only a control test but also for scientific purposes.

RVJ has been utilized in previous research [e.g., 8] to study the mechanisms of human movement since RVJ is a typical stretch-shortening cycle (SSC) exercise. During RVJ, the leg extensor muscles lengthen and shorten in turn. This behavior is called SSC action, which is characteristic of most natural activities (e.g.,., walking, running, jumping, and skiing) [2]. Fukashiro, et al. [8] examined the elasticity of the Achilles tendon and reported that elastic energy contributes 30% of calf muscle work in RVJ. Many researchers have used RVJ to study SSC action, which is recognized to enhance the performance better [5] and improve mechanical efficiency [12] compared with isolated pure concentric actions.

Previous studies have mainly focused on single joint muscle actions, not the whole movement of RVJ. Schwameder [15], however, proposed a research pyramid consisting of five levels of experimental biomechanical research and classification regarding validity and reliability: competition, training conditions, mimicking exercises, singular coordination components, and singular physical components. The lower levels of the research pyramid (e.g., singular physical components) have the greatest reliability but are difficult to apply in training and/or competition [15]. At the higher levels of the research pyramid (e.g., competition), experimental conditions cannot be sufficiently controlled, and thus reliability might be substantially reduced [15]. Mimicking exercises, which are located in the middle of the research pyramid, might be important tools since they have moderate validity and reliability. RVJ is considered a mimicking exercise of running and sprinting. Strategies to improve RVJ performance and mechanisms for achieving a greater jumping height have not yet been clarified. Therefore, the purpose of the present study was to clarify the key factors of kinetics and lower limb muscular activity to achieve greater jumping height during maximal RVJ.

Methods

Subjects

Eighteen male athletes (age: 20.7 ± 0.9 years, height: 1.79 ± 0.05 m, body mass: 83.2 ± 15.2 kg) were recruited from a group of university track-and-field athletes. All participants provided voluntary informed consent, and the experiment was approved by the ethical committee of the College of Humanities and Sciences, Nihon University.

Procedure and measurement

The subjects performed two series of RVJ, with a rest period of five min between the series, on a force platform (Kistler, Switzerland). RVJ included five continuous maximal vertical jumps. The subjects were instructed to jump as high as possible and to hold their arms on their hip.

During RVJ, ground reaction forces (GRF) were measured using a force platform (9281B, Kistler, Switzerland) at a sampling frequency of 1000 Hz. Sagittal plane kinematics were obtained using a high-speed video camera (GC-P100, JVC, Japan) at a frame rate of 300 fps. Calibration marks were placed around the force platform at a space of 1 m.

Electromyography (EMG) was recorded using active surface electrodes (SX-230, Biometrics, UK) at a sampling frequency of 1000 Hz from the gluteus maximus (GM), rectus femoris (RF), vastus lateralis (VL), gastrocnemius (GA), tibialis anterior (TA) muscles. The inter-electrode distance was 20 mm. To achieve good electrode-skin contact, the skin was shaved and cleaned with alcohol prior to the attachment. In accordance with SENIAM guidelines [9], electrodes were placed longitudinally over the muscle belly between the center of the innervation zone and the distal tendon of each muscle. EMG data were synchronized with kinematics and GRF data based on an LED signal. Before the trials, the subjects performed maximal voluntary contraction (MVC) to normalize the EMG signals.

Data analysis

Two-dimensional coordinates of seven anatomical landmarks (toe, head of the fifth metatarsal bone, heel, lateral malleolus, lateral epicondyle, greater trochanter, and upper margin of the sternum) were obtained using video analysis software (Frame-DIAS V, DKH, Japan) at a sampling frequency of 100 Hz. Coordinate data were smoothed using a Butterworth low-pass digital filter at the optimum cutoff frequency, which was determined by residual analysis of each point [18]. The center of mass and moment of inertia for the body segments were obtained according to the estimations by Ae, et al. [1]. Joint torque at the ankle, knee, and hip was calculated using the inverse dynamics method. The mechanical work of each joint was calculated by integrating the joint torque power, which was the inner product of joint torque and joint angular velocity.

The ground contact time and flight time were determined based on vertical GRF. Jumping height was calculated by the following equation:

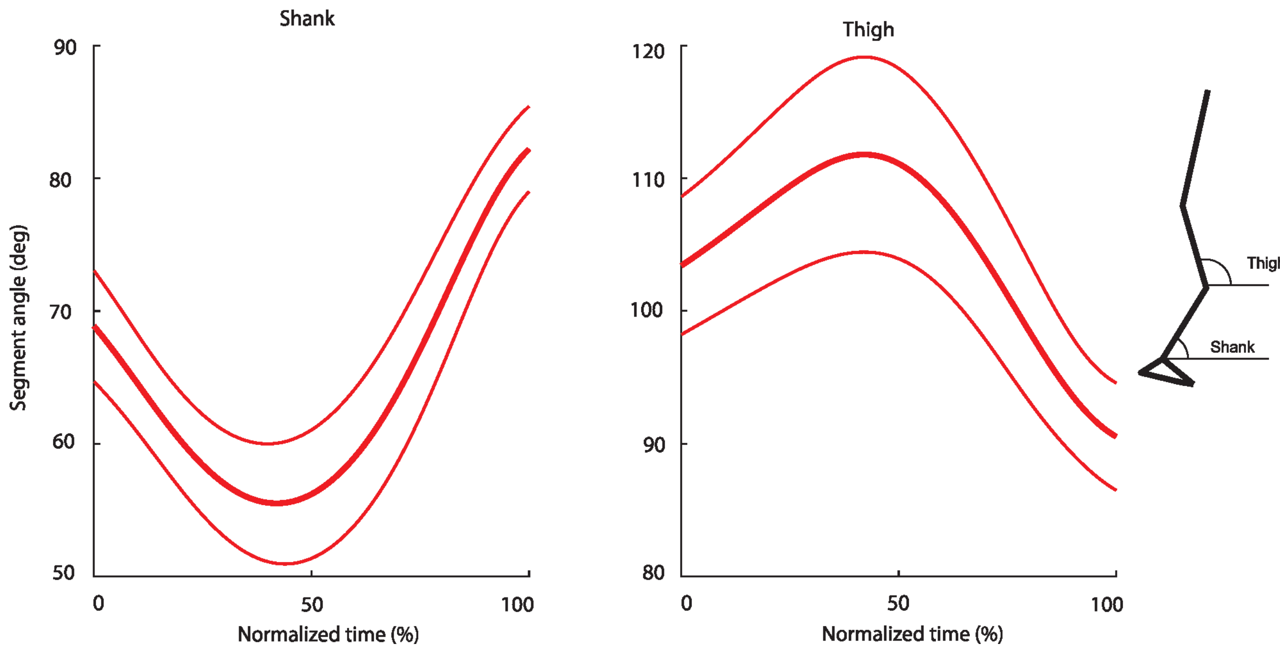

Figure 1 – Mean (±SD) of angle of the shank and thigh segments during ground contact

$$H = 1/8 \cdot g \cdot t^2 \qquad \text{(Eq. 1)}$$

where H – jumping height, g – gravitational acceleration, and T – flight time [6].

EMG data were high-pass filtered with a Butterworth digital filter at a cut-off frequency of 10 Hz to eliminate low-frequency motion artifacts. Next, EMG data were rectified and low-pass filtered using a Butterworth digital filter at 15 Hz to obtain the envelope. The average value of the EMG envelope during ground contact was then obtained.

Statistics

The results were expressed as mean ± standard deviation (SD). Pearson's correlation coefficient was used to determine the relationship between the measured biomechanical variables and jumping height. The level of statistical significance was set at $p < 0.05$.

Results

The mean jumping height was 0.34 ± 0.08 m (range: 0. 23 m to 0.49 m) and contact time was 0.20 ± 0.02 s. The relationship between jumping height and contact time was not statistically significant (r = –0.18, n. s.).

Figure 1 illustrates the averaged angles of the shank and thigh during ground contact. The greatest forward inclination of the shank was 69 ± 4 deg, which was not significantly related to jumping height (r = –0.42, n.s., Fig. 2). The greatest backward incline angle of the thigh was

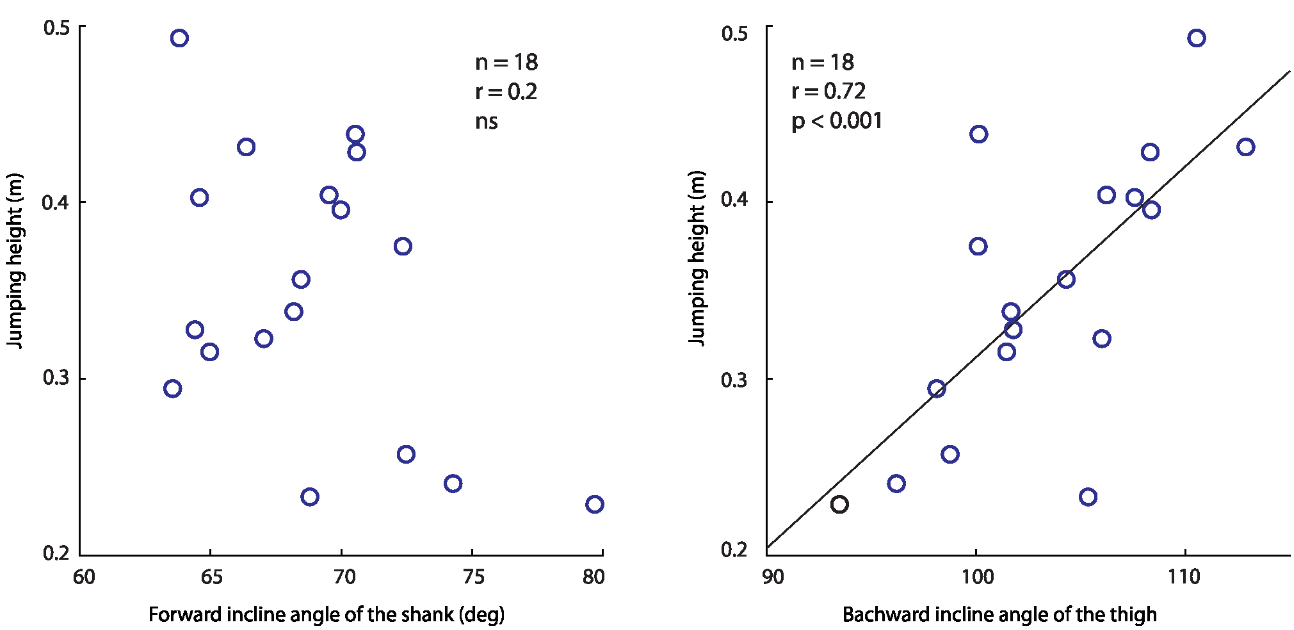

Figure 2 – Relationships between jumping height and forward incline angle of the shank and backward incline angle of the thigh

Table 1 – Mean (±SD) of kinetics variables and correlations with jumping height

Variable	Mean ± SD	r
Plantarflexion angular impulse (Nm • s • kg^{-1})	0.36 ± 0.09	0.35
Knee extension angular impulse (Nm • s • kg^{-1})	0.27 ± 0.10	0.61**
Hip extension angular impulse (Nm • s • kg^{-1})	0.17 ± 0.10	0.19
Positive mechanical work of the ankle joint (J • kg^{-1})	1.44 ± 0.30	0.73***
Positive mechanical work of the knee joint (J • kg^{-1})	0.65 ± 0.27	0.60**
Positive mechanical work of the hip joint (J • kg^{-1})	0.69 ± 0.44	0.29
Negative mechanical work of the ankle joint (J • kg^{-1})	–0.77 ± 0.26	–0.28
Negative mechanical work of the knee joint (J • kg^{-1})	–0.72 ± 0.45	–0.24
Negative mechanical work of the hip joint (J • kg^{-1})	–0.30 ±0.15	–0.30

** $p < 0.01$. *** $p < 0.001$.

Table 2 – Mean (±SD) EMG and correlation with jumping height

Muscle	Mean ± SD (%MVC)	r
Gluteus maximus	37.6 ± 27.4	0.60**
Biceps femoris	34.1 ± 29.4	0.44
Rectus femoris	53.4 ± 30.9	0.54*
Vastus lateralis	58.7 ± 38.5	0.40
Gastrocnemius	45.3 ± 31.4	0.18
Tibialis anterior	17.2 ± 9.1	0.21

* $p < 0.05$. ** $p < 0.01$.

103 ± 5 deg, which was significantly correlated with jumping height ($r = 0.72$, $p < 0.001$, Fig. 2).

Table 1 demonstrates mean (±SD) of the kinetic variables and their correlation coefficients with jumping height. The angular impulse of the knee joint during the extension phase of ground contact was 0.27 ± 0.10 Nm • s • kg^{-1}, which correlated with jumping height ($r = 0.61$, $p < 0.01$). The positive mechanical work of the ankle and knee joints was 1.44 ± 0.30 J • kg^{-1} and 0.65 ± 0.27 J • kg^{-1}, respectively. Jumping height correlated positively with positive mechanical work of the ankle ($r = 0.73$, $p < 0.001$) and knee joints ($r = 0.60$, $p < 0.01$).

Table 2 demonstrates mean (±SD) relative EMG values and their correlation coefficients with jumping height. The EMG of the GM muscle was 37.6 ± 30.9% MVC, which correlated positively with jumping height ($r = 0.60$, $p < 0.01$). The EMG of the RF muscle was 53.4 ± 30.9% MVC, which also correlated positively with jumping height ($r = 0.54$, $p < 0.05$).

Figure 3 presents the mean EMG patterns of the GM, RF, BF, VL, GA, and TA muscles and respective joint angles and torques of the hip, knee, and ankle joints during ground contact. The GM and RF muscles showed similar activity, as they co-contracted from the beginning to the middle of ground contact. The hip joint showed two peak extension torques immediately after landing and at the middle of ground contact, whereas the peak flexion torque timed at the first half of ground contact. The RF and VL muscles, which are the primary knee extensors, showed similar patterns during ground contact, with peak activity during the first half of ground contact. The muscular activity of the BF and GA, which are knee flexors, was smaller than that of the knee extensors. The GA muscles, which are also plantarflexor, showed the highest activity during the first half of ground contact, and then decreased until toe-off. The TA showed low activity during ground contact. The ankle joint exerted plantarflexion torque, which peaked at the middle of ground contact.

Discussion

The major findings of the present study were as follows: 1) there was no significant relationship between contact time and jumping height, 2) mechanical work of the ankle and knee joints was positively correlated with jumping height, 3) knee extension angular momentum was positively correlated with jumping height, 4) the maximal backward incline angle of the thigh was positively correlated with jumping height, and 5) EMGs of the GM and RF were positively correlated with jumping height.

Consistent with previous reports for RVJ [20] and DJ [11], there was no significant relationship between contact time and jumping height. A shorter contact time implies a shorter coupling time between eccentric and concentric action. As a shorter coupling time is important for enhancing performance during the concentric phase [5], it is likely that a shorter contact time enhances jumping height. However, the present study did not find any evidence to support this. If the contact time is too short, it may not exert sufficient force on the ground. Kajitani, et al. [11] examined the optimal contact time to achieve the greatest jumping height during DJ from 30 cm and reported that the optimal contact time differed based on individual characteristics. Furthermore, they suggested that a shorter a contact time is not necessary to achieve a greater jumping height, but did not examine kinematics or kinetics [11].

Positive mechanical work of the ankle joint was greatest in the lower limb joints and correlated positively with jumping height. Earlier studies [3, 13] have suggested that jumping exercises rely heavily on the triceps surae musculature and Achilles tendon. As the foot is the sole segment contacting the ground, it is assumed that the plantarflexor muscles play an important role in jumping. However, the EMG values of the plantarflexor muscles did not correlate with jumping height. Bobbert, et al. [4] reported that mechanical energy is transported from the knee to the ankle joint via the GA muscle. Our findings suggest mechanical energy transportation from the knee to ankle joint. Greater mechanical work of the ankle joint could be achieved by transported mechanical energy from the proximal joints via the GA muscle.

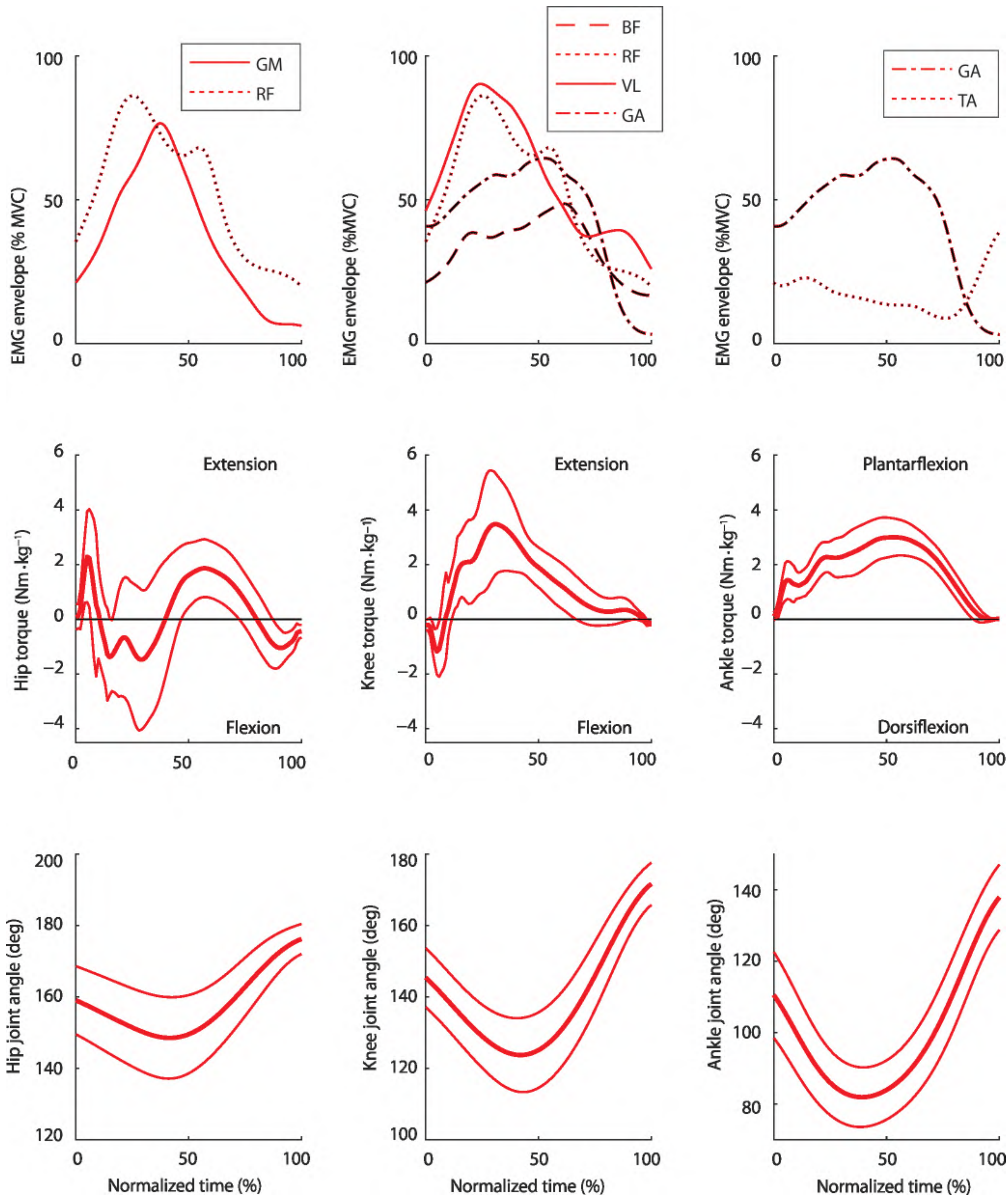

Figure 3 – Electromyography (EMG) envelopes of the gluteus maximus (GM), rectus femoris (RF), biceps femoris (BF), vastus lateralis (VL), gastrocnemius (GA), and tibialis anterior (TA) muscles and mean (±SD) of the hip, knee, and ankle joints torques during ground contact

The present study found that positive mechanical work and angular momentum of the knee joint in the eccentric phase correlated with jumping height, suggesting that the knee joint plays an important role in vertically accelerating the body. Seki, et al. [16] also suggested that the knee extensors contribute to jumping height in maximal RVJ, but they did not mention the mechanisms. In fact, movement of the knee joint controls the thigh and shank. The present study also reported a significant positive correlation between jumping height and maximal backward inclination of the thigh. However, the maximal forward incline of the shank did not correlate with jumping height. Work by Zushi and Takamatsu [21] implied that the angular displacement of each lower limb joint should be greater and, therefore, more muscles should be activated to achieve a great jumping height. These results suggest that the backward inclination angle is a key factor for achieving a greater jumping height. Rotating the thigh forward more after rotating the thigh backward could be an effective movement for raising the whole body's center of mass. This rotation of the thigh could be caused by the knee extensors, and a significant association between the jumping height and extension angular momentum of the knee joint would provide evidence for this.

The present study also reported that the EMGs of the GM and RF muscles correlated positively with jumping height, whereas the mechanical work and extension angular impulse of the hip joint were not correlated. The inverse dynamics determined the net joint torque, which ignored the co-contraction of the agonist and antagonist muscles [17]. The envelopes of the GM and RF muscles overlapped during the ground contact phase, which suggests that co-contraction occurred between the hip extensor and flexor. Thus, the torque and mechanical work of the hip joint could have been underestimated due to the limitations of inverse dynamics. However, it is known that co-contraction stabilizes joints [19], which may contribute to the stability of upper body posture. Another possible interpretation of the overlap in these muscles is co-activation. A generator of mechanical energy could play a role via the GM muscle transferring mechanical energy to the knee joint via the RF muscle. Prilutsky [14] reported that co-activation of a one-joint agonist and two-joint antagonist causes the transfer of mechanical energy from proximal to distal joints via two-joint muscles. It is difficult to verify and/or identify these two possibilities. However, the knee and hip joints would play important roles in achieving greater jumping height.

In conclusion, the knee joint plays an important role in achieving a greater jumping height. By rotating the thigh segment forward, the RF generates greater knee extension torque and greater positive mechanical work, and this work vertically accelerates the jumper's body to increase jumping height.

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