The Effects of Ankle Restriction on the Multijoint Coordination of Vertical Jumping

Hiroshi Arakawa,1 Akinori Nagano,2 Dean C. Hay,3 and Hiroaki Kanehisa4

1Japan Institute of Sports Sciences; 2Kobe University; 3Nipissing University; 4National Institute of Fitness and Sports in Kanoya

The current study aimed to investigate the effect of ankle restriction on the coordination of vertical jumping and discuss the influence of energy transfer through m. gastrocnemius on the multijoint movement. Eight participants performed two types of vertical jumps: a normal squat jump, and a squat jump with restricted ankle joint movement. Mechanical outputs were calculated using an inverse dynamics analysis. Custom-made shoes were used to restrict plantar flexion, resulting in significantly (P < .001) reduced maximum power and work at the ankle joint to below 2% and 3%, while maintaining natural range of motion at the hip and knee. Based on the comparison between the two types of jumps, we determined that the ankle restriction increased (P < .001) the power (827 ± 346 W vs. 1276 ± 326 W) and work (92 ± 34 J vs. 144 ± 36 J) at the knee joint. A large part of the enhanced output at the knee is assumed to be due to ankle restriction, which results in the nullification of energy transport via m. gastrocnemius; that is, reduced contribution of the energy transfer with ankle restriction appeared as augmentation at the knee joint.

Keywords: energy transfer, plantar flexion, gastrocnemius, simulation, biarticular

Vertical jumping is a fundamental human movement involving all joints of the lower limb. Preceding studies have investigated aspects of the multijoint coordination and activation of muscles required to achieve jumping height.1,2 However, investigating the behavior of each muscle in the musculoskeletal system has been somewhat challenging in vivo,3 mainly because the multijoint movement of jumping is quite complex and involves a number of muscles including biarticular muscles.

To understand the mechanism of multijoint movements in vertical jumps, previous studies frequently used nonexperimental approaches, such as modeling and simulation, primarily because the work outputs of individual muscles can be estimated by using a musculoskeletal model. Quantification of each muscle’s behavior using simulation has revealed several interesting features related to the multijoint coordination of vertical jumps. For example, modeling studies have discussed the functional roles of biarticular muscles in multijoint human movements.4 In particular, the effect of energy transportation, which is one of the important behaviors attributable to the specific structures of a biarticular muscle, has been extensively discussed in regard to vertical jumping.5–7 In accordance with the definition proposed by Prilutsky & Zatsiorsky,8 part of the energy generated by proximal muscles appears as mechanical work at a distal joint due to energy transfer through biarticular muscles.9 Although energy transfer itself yields relatively small or no improvement in jumping height,6,7,9 it contributes to the coordination of the multijoint movement through redistribution of each joint’s work output.8–10 In this regard, a relatively small number of studies has investigated the effects of energy transport on vertical jumping in an experimental setting, probably because of the difficulties mentioned above.1,8–10 Also, no studies have experimentally determined the influence of biarticular muscles on the measured mechanical output at each joint in vertical jumping. A direct investigation of net joint output will further our understanding of the coordination of multijoint musculoskeletal dynamics.

In this study, we investigated the effect of restricting ankle joint movement on the multijoint coordination of vertical jumping. We chose this approach because, during simultaneous extensions of the lower limb joints in vertical jumping, biarticular m. gastrocnemius acts as an agonist at the ankle joint resulting in positive work, whereas this muscle also acts as an antagonist at the knee resulting in negative work (this is the phenomenon of “energy transport”).5,11 A restriction of plantar flexion
during vertical jumping would decrease the contribution of m. gastrocnemius to both the ankle and knee joints. Therefore, by comparing the mechanical output of the knee joint between the normal and ankle-restricted vertical jumps, we will be able to consider the contribution of m. gastrocnemius to the knee. The purposes of the current study were to investigate the effect of ankle restriction on the coordination of vertical jumping and discuss the influence of energy transfer through m. gastrocnemius on the multijoint movement.

Methods

Subjects

Eight healthy male participants participated in this study. Their mean (± SD) age, height, body mass, and maximal vertical jump height was 24.1 (± 4.1) years, 1.722 (± 0.069) m, 64.4 (± 9.7 kg), and 0.292 (± 0.035) m, respectively. The performance of vertical jumping is the maximum height of COM from the toe-off. Informed consent was obtained from all participants after explaining the purpose and design of the study. This study was approved by the Ethics Committee of the University of Tokyo.

Experimental Tasks and Materials

The participants performed two types of vertical jumps: a normal squat jump with bare feet (NJ), and a squat jump with restricted ankle joint movement (ARJ). The initial joint angles of the knee and hip were identical between the NJ and ARJ for each subject. Participants were asked to jump as high as possible without utilizing a countermovement and with their hands on their iliac crests.

Custom-made shoes were used to restrict ankle joint movement in the ARJ (Figure 1). Light (0.07 kg) rubber sandals (Figure 1, upper picture) were cut mediolaterally 0.08 m anterior to the lateral malleolus. We performed a preliminary study to confirm that the work output of the plantar flexion was restricted when the custom-made shoes were worn. In the pilot study, the subjects were instructed to perform a vertical jump putting their weight on the heel side (without contacting their toes with the ground) throughout the jumping movement, because the ground reaction force (GRF) was generated in line with the center of the ankle joint. Even when the shoes were worn, the plantar flexion motion was not completely restricted; angular displacement at the ankle joint was approximately 15 degrees on average. Nevertheless, this angular displacement at the ankle joint is a minor issue as the primary reason for using the shoes was to restrict the mechanical output of power and work. When the subjects successfully jumped without plantar flexing (ie, without contacting their toes with the ground), the ankle joint work was suppressed to less than 1% of the whole body’s work. Regarding the knee and hip joint, wearing the shoes did not affect the natural joint extension.

Experimental Procedure

All subjects participated in a practice session before the testing day to become familiarized with the experimental movement. On the testing day, the subjects performed light aerobic exercises and stretches to warm up. The subjects performed five trials of NJ and ARJ in a random order. To make the initial flexion angles of the hip and knee uniform between the NJ and ARJ trials, these angles were recorded in the sagittal plane. The NJ and ARJ trials were performed in a random order, with a 2-min rest period between two successive trials. A trial was repeated in the case of failure; for example, when the subject’s toes made contact with the ground in ARJ or when obvious countermovements were used.

Measurement of the Kinematic and Force Data

Kinematic data were measured using a 3-dimensional motion capture system (HAWK Digital System, Motion Analysis Corporation, Santa Rosa, CA, USA). The subjects were marked with reflective markers (diameter of 20 mm) at the following anatomical landmarks to create a link segment model: shoulder, hip, knee, ankle, and toes on the right and left sides of the body. These data were recorded using six cameras at 200 Hz.

The vertical, horizontal, and longitudinal direction components of the GRF and the center of pressure (COP) were measured using a force platform (9281B, Kistler, Switzerland). The GRF and COP data were recorded at 1000 Hz using an analog-to-digital converter (Eagle hub3, Motion Analysis) synchronized with the position data.

Data Analysis

The position data recorded by the motion capture system were smoothed using a low-pass digital filter
A 2-D link segment model was constructed from the position data. Right and left coordinates were averaged for each landmark (ie, right and left shoulders, hips, knees, ankles, and toes). Three joint angles (hip, knee, and plantar angles) were defined from the 2-D coordinates. The mass of each segment and moment of inertia parameters reported by Winter (1990) were used and personalized (scaled) for each subject. The upper body (head, arms, and trunk) was modeled as one segment. Net intersegmental forces and joint moments were calculated using a standard inverse dynamics procedure. Joint extension was defined as the positive direction (plantar flexion for the ankle joint). Joint power was calculated as the product of net joint moment and angular velocity. Joint work was calculated using the time integration of joint power. The highest jump of each trial condition was selected for further analysis.

A two-tailed paired $t$ test was used to determine if the mean values of the jump height, minimum height, and height at takeoff, and maximal vertical GRF were different between the normal and the ankle restricted conditions (Table 1). Regarding the parameters of each joint, ANOVA with Scheffe’s post hoc analysis was used to determine if the mean values of the maximal joint flexion angles, joint flexion angles at takeoff, maximal joint power, and the joint work of each joint were different between the two conditions (Table 2 and Table 3). The significance level was set at $P < .05$.

**Results**

Restricting the ankle joint significantly ($P < .001$) reduced the maximum power and work at the ankle to below 2% and 3%, respectively, of the normal vertical jumping values (Table 3). Although a certain degree of angular displacement at the ankle joint was observed in the ARJ condition (Table 2 and Figure 2A), the maximum value of the joint moment was less than 10% of NJ condition (Figure 2B).

The restriction of the ankle joint significantly ($P < .001$) decreased the maximum ankle flexion angles, but did not affect the maximum hip and knee flexion angles (Table 2). Throughout the jumping movement, the behaviors of the knee and hip joints were similar between the two conditions as shown in the stick figures (Figure 3). The time courses of COM height and vertical GRF (Figure 3) were also similar between the conditions, as indicated by the error bar ($\pm 2$ SD) overlap. The only exception was with COM height just before take-off. From the data, it is apparent that restriction of ankle joint did not disturb the natural jumping movement except for the ankle joint.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Major parameters of jumping performance. The mean and standard deviation values of the subjects are shown for each condition.</th>
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<td></td>
<td><strong>NJ</strong></td>
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<tr>
<td>COM jump height (m)</td>
<td>0.292 ± 0.035</td>
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<tr>
<td>COM minimum height (m)</td>
<td>0.538 ± 0.055</td>
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<tr>
<td>COM height at takeoff (m)</td>
<td>1.105 ± 0.059</td>
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<tr>
<td>Maximal vertical GRF (N)</td>
<td>1311 ± 220</td>
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$*P < .05$, $**P < .01$, $***P < .005$, $****P < .001$, significant difference between NJ and ARJ.

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<tr>
<th>Table 2</th>
<th>The mean and standard deviation values of maximal flexion angles and take-off angles of each joint for the NJ and ARJ conditions.</th>
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<tr>
<td></td>
<td><strong>NJ</strong></td>
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<tr>
<td>Maximal flexion angle (deg)</td>
<td></td>
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<tr>
<td>Hip</td>
<td>132 ± 15</td>
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<tr>
<td>Knee</td>
<td>103 ± 12</td>
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<tr>
<td>Ankle</td>
<td>11 ± 7</td>
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<tr>
<td>Flexion angle at take-off (deg)</td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>15 ± 9</td>
</tr>
<tr>
<td>Knee</td>
<td>6 ± 4</td>
</tr>
<tr>
<td>Ankle</td>
<td>−54 ± 4</td>
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</table>

$*P < .05$, $**P < .01$, $***P < .005$, $****P < .001$, significant difference between NJ and ARJ.
Significant ($P < .001$) augmentations of the peak positive power and work at the knee joint were measured with restriction of plantar flexion (Table 2). When the shoes were worn, the peak knee joint power significantly increased (+54% on average; NJ, 827 ± 346 W vs. ARJ, 1276 ± 326 W; Table 2). Furthermore, the peak values of the summated joint power of the knee and hip joint work ($J$) significantly increased with ankle restriction (+24% on average; NJ, 1789 ± 370 W vs. ARJ, 2215 ± 394 W; Table 2). Regarding hip joint power, no significant difference was found in the peak values between NJ (1217 ± 245 W) and ARJ (1174 ± 231 W). Similar to the case of power output, the net joint work at the knee also increased with ankle restriction (+57%
on average; NJ, 92 ± 34 J vs. ARJ, 144 ± 36 J; Table 2). Regarding the hip joint, the net positive work decreased ($P < .001$) with ankle restriction (−19% on average; NJ, 236 ± 58 J vs. ARJ, 191 ± 43 J).

The negative moment and power values of the knee joint just before take-off (about 60 ms before take-off) were remarkable in normal jumping but decreased when ankle joint movement was restricted (Figure 2B and 2C). In contrast to the knee, the development of negative moment and negative power increased in the hip joint with restriction of the ankle joint (Figure 2B and 3C).

**Discussion**

The jumping movements of NJ and ARJ conditions were approximately similar except for the ankle joint, resulting in significantly restricted mechanical output at the ankle in the ARJ condition. The ankle restriction resulted in a significant increase of the power and work at the knee joint, as well as the summed power of the knee and hip.

This study’s most important finding is that restricting plantar flexion results in the increased power and work at the knee joint. A presumable explanation for the enhanced output at the knee is the nullification of energy transfer via m. gastrocnemius, which occurs from the knee to ankle in normal vertical jumps. The biarticular m. gastrocnemius acts as an energy transporter during the movement of jumping; that is, the energy generated by the knee extensors can be partly used as the mechanical work output at the ankle joint.\(^1,7,11\) The timing with which the augmentation of net knee power occurred in the current study (during the last 60 ms of the push-off; Figure 2C) approximately corresponds to the timing of energy transfer reported in a preceding study.\(^1\) Furthermore, in the current experiment, the negative knee power observed in the normal jumps (at the later part of the push-off phase; Figure 2C) decreased with ankle restriction. According to Bobbert and van Ingen Schenau (1988), eccentric force generation at the knee joint seen in normal vertical jumping is due to antagonistic behavior of the biarticular m. gastrocnemius.\(^1\) This observation indicates that the reduced contribution by m. gastrocnemius associated with ankle restriction contributed to the marked reduction of negative knee power, which leads to the augmentation of net output at the knee in ARJ. These consistencies support the idea that the nullification of energy transportation with ankle restriction largely contributed to the enhanced output at the knee joint.

The novelty of the current study is that we attempted to experimentally investigate the influence of energy transfer via a biarticular muscle on the net mechanical output at each joint in vertical jumping. In the literature, there had been a controversy whether the biarticular muscles contribute to the transfer of energy from proximal to distal joints. A prior study has suggested that the transfer does not exist.\(^6\) Observations of the current study, however, agree with several studies which suggest that energy is actually transported during vertical jumping.\(^1,5,7,8,10\) Musculoskeletal modeling has been used to quantify the work outputs done by biarticular muscles at each joint.\(^5,7,11\) Alternatively, some studies have inferred the influence of energy transfer using experimental approaches such as electromyography.\(^1,8–10\) As far as we know, the current investigation is the first case which experimentally determines the influence of biarticular muscles on the measured mechanical output at each joint in vertical jumping.

Several factors may have affected the current observations. First, some differences existed in the kinetics and kinematics between NJ and ARJ. The decrease in joint work at the hip associated with ankle restriction (Table 3) is important as it indicates that the activation level of biarticular thigh muscles might have changed, that is, increased activation of m. rectus femoris or decreased activation of mm. hamstring muscles. These changes are relevant to the augmentation at the knee joint in addition to the nullification of energy transfer via m. gastrocnemius. However, we consider the changes in activation levels of the thigh muscles as small, because the hip joint power did not decrease significantly with ankle restriction (Figure 2C and Table 3). A more plausible explanation for the decrease in hip joint work is the limited range of joint extension in ARJ. Although no significant difference was found in the initial hip flexion angles between ARJ and NJ, the hip angle at take-off was more flexed in the ARJ (Table 2). Therefore, the range of joint extension at the hip for generating the mechanical work was greater in NJ than ARJ. Moreover, the maximal knee flexion angle slightly decreased with ankle restriction, though no statistically significant difference was found between the two conditions (Table 2). Nevertheless, these results do not preclude the current interpretation because the enhancement of power and work at the knee with the ankle restriction cannot be explained by the decreased maximal knee flexion angle and consequent reduction of joint ROM (which contributes to a decrease in work at the knee). Considering these points, the small changes in the jumping movements associated with ankle restriction do not markedly influence the interpretation of the current findings.

Second, although the jumping movements were similar between the two conditions, some differences might exist in the activities of the muscles. Regarding the activity of the knee and hip extensors, we consider the changes associated with ankle restriction as small. This assumption is based on the fact that both jumps were performed with maximum voluntary efforts. In addition, co-contraction might have occurred at the ankle joint in the ARJ, permitting m. gastrocnemius to generate some extent of force, whereas the net moment at the ankle was negligible. In this regard, the activation level of the triceps surae including m. gastrocnemius would be relatively small because the moment-generating capability of the dorsiflexors is roughly one third of the plantar flexors.\(^13\) For this reason, the absolute value of the force generated by m. gastrocnemius would be small when wearing the shoes, even if a certain degree of co-contraction occurred at the ankle joint. Accordingly, a large part of
the augmentation at the knee can be explained by the nullification of energy transportation. Nevertheless, if we had examined the EMG of relevant muscles, we could have assessed the validity of the assumption that the two jumps were similar, and it is a limitation of the current study.

In summary, we investigated the effect of ankle restriction on the multijoint coordination of vertical jumping. Based on the comparison between the normal and ankle-restricted jumps, we determined that the restriction of ankle joint movement during vertical jumping increased the power and work output at the knee joint. A large part of the enhanced output at the knee is assumed to be due to ankle restriction, which results in the nullification of energy transportation via m. gastrocnemius; that is, reduced contribution of the energy transfer with ankle restriction appeared as augmentation at the knee joint.

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References