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Contribution of the lower extremity joints to mechanical energy in running vertical jumps and running long jumps

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The energy contribution of the lower extremity joints to vertical jumping and long jumping from a standing position has previously been investigated. However, the resultant joint moment contributions to vertical and long jumps performed with a running approach are unknown. Also, the contribution of the metatarsophalangeal joint to these activities has not been investigated. The objective of this study was to determine the mechanical energy contributions of the hip, knee, ankle and metatarsophalangeal joints to running long jumps and running vertical jumps. A sagittal plane analysis was performed on five male university basketball players while performing running vertical jumps and four male long jumpers while performing running long jumps. The resultant joint moment and power patterns at the ankle, knee and hip were similar to those reported in the literature for standing jumps. It appears that the movement pattern of the jumps is not influenced by an increase in horizontal velocity before take-off. The metatarsophalangeal joint was a large energy absorber and generated only a minimal amount of energy at take-off. The ankle joint was the largest energy generator and absorber for both jumps; however, it played a smaller relative role during long jumping as the energy contribution of the hip increased.

Keywords: energy, long jump, joint power, vertical jump.

Introduction

Mechanical energy produced by muscles enables movement of the body during athletic activities. The maximal jump height or distance obtained by an athlete is largely dependent on the mechanical energy input or work performed before take-off to translate and rotate the centre of mass of the athlete. Therefore, it is important to understand the mechanical energy generation and absorption during jumping activities to provide further insight into athletic performance of these activities.

Energy generation and absorption can be calculated and studied using two main methods, the segmental energy method or the joint energy method. The segmental energy method is useful in determining the magnitudes and destinations of mechanical energy production during athletic activity. However, when trying to understand athletic performance, it is also important to determine the sources of the energy production, as the sources can be modified by training or external factors such as footwear.

The joint energy method allows the determination of the magnitudes and locations of the sources of mechanical energy absorption or generation during athletic activities. Analysis of resultant joint moments and joint energy during jumping activities indicate that, for each joint, there are phases when energy is absorbed and phases when energy is produced. If the absorbed energy is dissipated and not stored for later re-use, it could be speculated that a reduction of such energy absorption might lead to an increase in performance.

Most studies of joint energy production during vertical jumping have concentrated on comparisons of different jumping styles and the influence of bi-articular muscles, and have generally investigated either a
counter-movement or squat jump from a standing position (Hubley and Wells, 1983; van Ingen Schenau et al., 1985; van Soest et al., 1985; de Graaf et al., 1987; Fukashiro and Komi, 1987; Robertson and Fleming, 1987; Bobbert and van Ingen Schenau, 1988; Pandy and Zajac, 1991; Prilutsky and Zatsiorsky, 1994). There are many athletic activities (e.g. basketball) where jumping performance is critical and where vertical jumps are performed not only from a standing position, but also from a running approach. There is a lack of information regarding the mechanical energy contributions of the joints to vertical jumps performed with a running approach.

Most studies of running long jumps have been concerned with approach strategies and jumping technique (e.g. Hay et al., 1986; Hay, 1988; Hay and Nohara, 1990). Very few studies have investigated resultant joint moments or joint energy produced during long jumping (Robertson and Fleming, 1987; Horita et al., 1991; Prilutsky et al., 1993). Of these, only Prilutsky et al. (1993) investigated long jumping from a running approach, and they only presented data for the knee joint determined from one jump. There have been surprisingly few studies into joint energy production during long jumping; as a result, very little is known about the energy contributions of the lower extremity joints to the activity of long jumping.

The objective of this study was to determine the mechanical energy contributions of the various joints of the lower extremities, including the hip, knee, ankle and metatarsophalangeal joints, to running long jumps and running vertical jumps.

Methods

Subjects

Nine subjects participated in this study. Five subjects, who were all men’s university basketball team members, were recruited for the vertical jump test (mean ± s: age 21.0 ± 1.9 years; height 190 ± 8 cm; body mass 83.5 ± 10.1 kg). In addition, four male long jumpers with personal best jumps of 7.05-7.53 m also volunteered (age 23.0 ± 2.6 years; height 176 ± 2 cm; body mass 77.5 ± 1.3 kg). Informed written consent was obtained from all subjects.

Protocol

Ten vertical jumps were recorded for each basketball player. The vertical jumping activity consisted of a one-legged jump and reach that was similar to a basketball player driving to the basket. Each subject wore his own shoes. For the jump, the subjects were allowed a maximum approach distance of 15 m, although they all chose an approach distance of only a few metres. Six trials were measured for each long jumper. The long jumpers accelerated for approximately 15 m before take-off where data were collected. Since the data were collected in the laboratory with a foam landing pit, all long jumps were performed sub-maximally to prevent injury. The average speed of the long jumpers (calculated over a 1.93 m interval where data were collected) ranged from 6.1 to 6.6 m s⁻¹. Each subject performed the long jumps in his own training shoes.

Kinetic data were collected with a force platform at 1000 Hz (Kistler, Winterthur, Switzerland). Kinematic data were collected simultaneously with the kinetic data using a four-camera video system (Motion Analysis Corp., Santa Rosa, CA) at 200 Hz. Reflective markers of 1 cm diameter were placed on the toe, the head of the fifth metatarsal, the heel, the lateral malleolus, the lateral epicondyle, the greater trochanter and the shoulder. The markers were chosen to represent the ankle, knee and hip joints and divided the body into five rigid segments: forefoot, rearfoot, shank, thigh and trunk.

Analysis

A two-dimensional sagittal plane analysis was performed on the data. Velocities and accelerations were calculated from smoothed positional data (zero-lag, fourth-order, low-pass Butterworth filter with a cut-off frequency of 8 Hz). The 8 Hz cut-off frequency was chosen as the best representation of the raw signal after visual inspection of a variety of different cut-off frequencies. This cut-off frequency is similar to those reported in the literature for these types of activities (Hubley and Wells, 1983; Fukashiro and Komi, 1987; Robertson and Fleming, 1987). The kinetic data were also smoothed with a zero-lag, fourth-order, low-pass Butterworth filter but with a cut-off frequency of 100 Hz.

Each subject’s body mass and height as well as lengths of the foot, shank and thigh segments were measured for calculation of the necessary inertial parameters using regression equations from Zatsiorsky and Seluyanov (1983). Inverse dynamics (Bresler and Frankel, 1950) was used to calculate the resultant joint moments for each of the four joints of the lower extremity. The analysis assumed the resultant moment at the metatarsophalangeal joint was zero until the ground reaction force acted distally to the joint. This was based on the assumption that the inertial effect of the phalanges was negligible. Like Winter (1983), the convention was chosen so that the knee and hip extensor moments and ankle and metatarsophalangeal plantarflexor moments were positive.
Joint power was calculated from the following equation:

\[ P_j = M_j \omega_j \]

where \( P_j \) is the power of joint \( j \), \( M_j \) is the resultant moment of joint \( j \), and \( \omega_j \) is the angular velocity of joint \( j \). Positive power occurs during a concentric contraction and is referred to as 'energy generation', while negative power occurs during an eccentric contraction and is referred to as 'energy absorption'. Energy was determined by numerical integration (Adams, 1990) of the joint power curve.

To help decide how to distribute the force plate data to the two foot segments, a pilot study was performed on a single subject for whom force plate data were collected simultaneously with EMED pressure insole data (85 sensors, 2.0 cm², 100 Hz) (Novel GmbH, Munich, Germany). The pressure insole allowed the division of the vertical ground reaction force into forces at both the forefoot and rearfoot segments. The resultant metatarsophalangeal joint moment was then calculated using the vertical force measured on the forefoot by the pressure insole and a percentage of the total horizontal force (measured by the force plate) which was equal to the percentage of the vertical force (e.g. if 10% of the total vertical force acted on the forefoot, it was assumed that 10% of the total horizontal force also acted on the forefoot). The moment about the metatarsophalangeal joint due to the vertical force on the forefoot was determined by summing the individual moments created by the forces applied to each pressure sensor. This process was used by Morlock and Nigg (1991), who estimated horizontal and vertical forces on a multi-segment model of the human foot by combining force plate and pressure data.

A comparison of the resultant metatarsophalangeal moments calculated using force plate data and pressure data is shown in Fig. 1 for long jumping. The data presented are the averages of three trials. The root mean square difference between the resultant metatarsophalangeal moment determined using the two methods was 18.0 N m and the difference between the maximal moments was 5%. Similarly, a comparison of the joint powers calculated using the two different methods is shown in Fig. 2, where the values shown on the joint power curves represent energy values (energy calculated using force plate data only is shown by the bold line). The root mean square difference between the power curves was 44 W and the difference in energy calculated between the two methods was less than 1%.

![Figure 1](image1)

**Figure 1** Net metatarsophalangeal joint moment comparison between the moment calculated using force plate data (bold line) and the moment calculated using EMED pressure insole data (dotted line) during long jumping. The moment calculated using the force plate data assumed the metatarsophalangeal moment was zero until the ground reaction force acted distally to the metatarsophalangeal joint. The moment calculated using EMED pressure insole data assumed the same relative distribution of the vertical and horizontal components of the ground reaction force on the forefoot.

![Figure 2](image2)

**Figure 2** Net metatarsophalangeal joint power and joint energy comparison between calculations using force plate data (bold line) and calculations using EMED pressure insole data (dotted line) during long jumping. The energy values were determined from integration of the joint power curves.
for long jumping. Theoretically, the resultant metatarso-
phalangeal moment determined from EMED data
should be larger than the resultant moment determined
from force plate data for the initial part of stance, and
the resultant moments should be equal during the
latter part of stance. Thus the use of a single ground
reaction force to determine net moments at the meta-
tarsophalangeal joint appears justified; however, it may
lead to a slight underestimation of the meta-
tarsophalangeal joint moment.

A pilot study was performed in which the entire pro-
tocol was repeated and measurements were taken on
different days to determine the repeatability of the
metatarsophalangeal joint energy calculations. The root
mean square difference between the metatarsoph-
alangeal joint energy calculated on the two separate
days was 5.6 J for a group of five subjects. The sensivi-
ty of the marker location for the metatarsophalangeal
joint was determined by manipulating the position of
the marker in the anterior-posterior direction by up to
1 cm during data analysis. A 1 cm increase in anterior-
posterior placement of the marker resulted in an aver-
age reduction of 12-28% in the energy absorbed at the
metatarsophalangeal joint for the running vertical
jumpers and an average reduction of 18-27% for the
running long jumpers.

Results

Running vertical jump

The five subjects who performed the running vertical
jump had a wide range of stance times (0.23-0.35 s) as
a result of different jumping strategies. Figure 3 shows
the resultant metatarsophalangeal, ankle, knee and hip
moments plotted for each of the five subjects (averaged
over 10 trials). The net plantar flexor moments at the
metatarsophalangeal joint showed consistent patterns
across the five subjects, with maximum values of
75-150 Nm. The resultant ankle moment was consis-
tently plantar flexor in nature, with peak magnitudes
of 250-400 Nm for all subjects. The resultant knee

![Figure 3](image-url)
moments were also primarily extensor in nature, with small flexor activity during the very early and late parts of stance. The resultant hip joint moments were primarily extensor in nature, with peak magnitudes of 300-500 N m.

The metatarsophalangeal, ankle, knee and hip power curves are plotted for each vertical jumper in Fig. 4. Each curve is an average of 10 trials. All five subjects absorbed energy at the metatarsophalangeal joint during the last part of stance; the amount of energy absorbed ranged from 11 to 37 J. In all cases, the primary energy generator was the ankle joint. All subjects had an energy absorption period at the ankle during the first half of stance, followed by an energy generation period during the last half of stance; the energy generation period produced roughly twice the amount of energy that was absorbed. Because of the variability in resultant knee and hip moments, the power curves for these joints were also variable. For all subjects, both the hip and knee joints had periods of energy absorption and energy generation, but the patterns were inconsistent. In some subjects the hip was a net energy generator and the knee was a net energy absorber, whereas in others the result was reversed with the hip being a net energy absorber and the knee being a net energy generator (Table 1).

The relative contribution of each of the lower extremity joints to the energy absorbed and generated is presented in Fig. 5. The ankle joint was the largest energy generator and absorber during the stance phase of vertical jumping. The metatarsophalangeal joint accounted for approximately 16% of the energy

Figure 4 Average (over 10 trials) net joint power curves for the hip, knee, ankle and metatarsophalangeal joints. Data are plotted for each vertical jumper.
absorbed but did not contribute to the energy generated.

Running long jump

The take-off foot contact times of the four long jumpers ranged from 0.15 to 0.17 s. Figure 6 shows the net metatarsophalangeal, ankle, knee and hip moments plotted for each of the subjects (averaged over six trials). The net metatarsophalangeal moment was primarily plantar flexor in nature, with maxima ranging from 100 to 150 N·m. Unlike vertical jumping, which had only one dominant peak in the resultant ankle moment curve as a result of the active phase of the activity, the net ankle joint moment curves during long jumping had two distinct peaks. In addition to the large active peak, there was a slightly smaller initial peak which was a result of the large blocking force produced as the long jumpers contacted the ground. The net knee moments were primarily extensor in nature, with maxima of 250-300 N·m. The resultant hip joint moments were also extensor in nature, with maximum moments ranging from 400 to 650 N·m.

The metatarsophalangeal ankle, knee and hip power curves are plotted for each long jumper in Fig. 7. Each curve is an average of six trials. During long jumping, the metatarsophalangeal joint absorbed a large amount of energy (33-61 J). Both the ankle and the knee joints had initial energy absorption phases followed by energy generation phases, with the ankle joint energy being approximately twice the magnitude of the knee joint energy; both joints absorbed more energy than they

<table>
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<tr>
<th>Subject</th>
<th>MP joint Absorb</th>
<th>MP joint Generate</th>
<th>Ankle joint Absorb</th>
<th>Ankle joint Generate</th>
<th>Knee joint Absorb</th>
<th>Knee joint Generate</th>
<th>Hip joint Absorb</th>
<th>Hip joint Generate</th>
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<td>47.9</td>
<td>61.9</td>
<td>24.6</td>
<td>51.3</td>
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</table>

Figure 5 Average relative contribution of the metatarsophalangeal, ankle, knee and hip joints to the energy absorbed and generated during the stance phase of vertical jumping.
produced. The energy at the hip joint was highly variable across subjects and generally quite small (Table 2).

The relative contribution of each of the lower extremity joints to the energy absorbed and generated is presented in Fig. 8. Like vertical jumping, the ankle joint was the largest energy generator and absorber during the stance phase of long jumping. The metatarsophalangeal joint was responsible for approximately 15% of the energy absorbed and contributed very little to the energy generated.

Discussion

This study was designed to provide information regarding the mechanical energy contributions of the metatarsophalangeal, ankle, knee and hip joints to running vertical jumps and running long jumps. Since athletic performance is largely dependent on the mechanical energy which is produced at the joints, understanding the contributions of each of the various lower extremity joints may provide further insight into athletic performance of these activities.

The net joint moment and joint power patterns presented for the running vertical jump correspond reasonably well to the joint patterns in the literature (Fukashiro and Komi, 1987; Robertson and Fleming, 1987; Bobbert and van Ingen Schenau, 1988), although these previous studies investigated vertical jumping from a standing position. This indicates that similar techniques are used for a vertical jump with a running approach as a vertical jump from a standing position. Peak net moments at the ankle joint ranged from 250 to 400 Nm in this study. These values correspond to the peak values of approximately 275-300 Nm found by Bobbert and van Ingen Schenau (1988) and 225 Nm found by Robertson and Fleming (1987) for standing vertical jumps. The peak net moments of 150-300 Nm at the knee joint for running vertical jumps in this study are comparable to the peak values

Figure 6 Average (over six trials) resultant joint moment curves plotted for each joint to allow a comparison between the four long jumpers. Metatarsal = metatarsophalangeal.
Figure 7 Average (over six trials) net joint power curves for the hip, knee, ankle and metatarsophalangeal joints. Data are plotted for each long jumper.

Table 2 Average (over 6 trials) energy absorbed and generated (J) at the metatarsophalangeal (MP), ankle, knee and hip joints during the stance phase of the running long jump

<table>
<thead>
<tr>
<th>Subject</th>
<th>MP joint</th>
<th>Ankle joint</th>
<th>Knee joint</th>
<th>Hip joint</th>
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<tr>
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<td>12.4</td>
<td>1.1</td>
<td>32.4</td>
<td>15.3</td>
</tr>
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</table>

Stefanyshyn and Nigg
of 175 and 300 N m reported by Robertson and Fleming (1987) and Bobbert and van Ingen Schenau (1988), respectively. Peak net moments at the hip during standing vertical jumps of 300-375 N m have been reported in the literature (Fukashiro and Komi, 1987; Robertson and Fleming, 1987; Bobbert and van Ingen Schenau, 1988). Peak net moments at the hip in this study ranged between 300 and 500 N m for running vertical jumps.

Like the vertical jumping results, the net joint moment and power patterns for the long jump corresponded reasonably well with the joint patterns reported in the literature (Robertson and Fleming, 1987; Horita et al., 1991), even though these studies investigated long jumping from a standing position. Peak net ankle moments during running long jumps ranged between 250 and 400 N m, corresponding to the peak values of approximately 300 N m reported in the literature during standing long jumps (Robertson and Fleming, 1987; Horita et al., 1991). Peak net knee and hip moments have been reported to be approximately 150 and 400 N m, respectively, during standing long jumps (Robertson and Fleming, 1987; Horita et al., 1991). The peak net knee and hip moments for running long jumps in this study were 250-300 and 400-650 N m, respectively. The peak net joint moments found for the running long jumps are only slightly higher than the values reported in the literature for standing long jumps.

It appears, therefore, that jumping in either the vertical or horizontal direction from a standing position requires the same type of movement pattern as jumping from a running take-off. It may be that the movement pattern of the jump is somewhat predetermined and the increase in horizontal velocity before take-off does not have a large influence on this pattern.

The metatarsophalangeal joint had the same relative contribution to running vertical and running long jumps. It was a large net energy absorber, absorbing approximately 15-16% of the total energy absorbed by the lower extremity. The knee also had the same relative contribution to both types of jumps. It generated 25% of the total lower extremity energy and absorbed 31% during vertical and 28% during long jumping. Thus, it would appear that the function of the metatarsophalangeal and knee joints is similar for the two types of jump.

In contrast, the functions of the ankle and hip joints appear to be different for running vertical and running long jumps. The ankle joint was the largest energy generator and absorber for both types of jumps; however, the relative contribution it made to the two types of jumps was different. It was responsible for 53% of the energy generated by the lower extremity during vertical jumping and absorbed 36%. During long jumping, the ankle joint absorbed and generated almost the same relative amount, 47 and 49% respectively. Thus its function changed from a large net energy generator during vertical jumping to a small net energy generator during long jumping.

The hip joint was a net energy generator during both types of jump. However, the relative contribution it
made to the energy generated during long jumping was greater than during vertical jumping (36 vs 21%). It also absorbed less energy relative to the rest of the lower extremity joints during long jumping than during vertical jumping (10 vs 16%).

That the ankle joint was the largest energy generator for both types of jumps suggests that training regimens should pay particular attention to the development of the gastrocnemius and soleus muscles. The requirement of large hip extensor moments during the stance phase of long jumping indicates that development of the hip extensor muscles is also extremely important for long jumpers.

It has been shown that the metatarsophalangeal joint is one joint where energy is absorbed and no (or very little) energy is generated at take-off. This is because the metatarsophalangeal joint flexes as athletes roll onto the foot and does not extend until after take-off. Since no energy is generated at this joint during stance, this energy must be dissipated and lost. In terms of performance, this loss of energy would appear to be extremely inefficient. It is unknown which the exact functional requirement of the metatarsophalangeal joint is during jumping; however, it is speculated that this joint may provide a stabilizing effect during take-off. If the necessary stability could somehow be achieved without the large loss of energy at the metatarsophalangeal joint, the result may be a positive effect on performance. Further research into the influence of the metatarsophalangeal joint is required for a better understanding of its function during running jumps.

Acknowledgements

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References


