Biomechanical loading in the triple jump

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The triple jump is a demanding field event in which a jumper must tolerate extremely high impact forces while maintaining high horizontal speed. The present study was designed to clarify the mechanical loading characteristics and the role of neuromuscular function in the triple jump. Seven national triple jumpers (4 males, 3 females) volunteered to perform 3–6 jumps. The mean best performances were 14.32 ± 0.45 m and 11.90 ± 0.28 m for males and females, respectively. The three longest triple jumps for each jumper were selected for final analysis. The mean contact times were 0.139 s (hop), 0.157 s (step) and 0.177 s (jump). The largest ground reaction forces were observed in the step (15.2 times body weight), while the highest peak pressures were recorded under the heel and forefoot. The plantar pressure of the lateral side of the forefoot was highly related to the length of the triple jump ($P < 0.05$–0.01). In addition, electromyograms of both legs suggested that mechanical loading places high demands on the neuromuscular system, as characterized by the high rate of activation in the pre-activity phase followed by high eccentric activity. Thus, the high activities of the gastrocnemius, vastus lateralis and hip extensor muscles seem to play an important role in preventing unnecessary yielding of the jumper during the braking phase.

Keywords: electromyography, ground reaction force, plantar pressure.

Introduction

The goal of a triple jumper is to attain the greatest possible horizontal distance. The distance covered depends largely on the horizontal approach speed, and the extent to which this can be controlled, conserved and even apportioned over the three phases: the hop, the step and the jump (Dyson, 1962; Hay, 1993). An elite triple jumper should be able to reach average speeds of more than 10.4 m·s^{-1} during the last 5 m before the take-off (Susanka *et al.*, 1987), and to maintain as much of this speed as possible during the hop, the step and the jump. This is possible only by minimizing the braking forces, thus optimizing vertical velocity.

Take-off techniques differ significantly between athletes because of their individual physical characteristics. For example, the lengths of the different phases related to the total length of the jump vary between individuals (Susanka *et al.*, 1987). Good take-off tech-nique is needed to provide an efficient link between muscle actions and their timing when producing large forces in the optimal direction, if horizontal speed is to be maintained. This requires that a jumper must tolerate high impact forces with minimal decrease in horizontal speed. However, only a few studies have been published of ground reaction forces and foot pressures in the triple jump. Two separate peaks have been observed in the vertical force: 7.0–14.2 times body weight in the braking phase and 3.3–5.0 times body weight in the push-off phase of the contact (Ramey and Williams, 1985; Jin, 1989). In the horizontal direction, there may be more peaks, with the highest values around 2.6–3.0 times body weight (Ramey and Williams, 1985; Jin, 1989). Furthermore, Ramey and Williams (1985) observed high inter-individual variability in the timing and magnitudes of the ground reaction forces, although general patterns are similar across jumpers. Pressure transducers implanted in the shoe have recorded the highest peak pressures under the heel, big toe and the first metatarsal during the hop and step (Nicol, 1977; Milani and Hennig, 1992). It has also been suggested

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that the high incidence of lower leg injuries may be due to large peak pressures in various regions of the foot in the triple jump (Milani and Hennig, 1992).

It is reasonable to assume that neuromuscular control and performance are challenged by those large forces and plantar pressures observed in triple jumping. Thus, the present study was designed to assess neuromuscular function and impact loads in the triple jump with a specific focus on the interaction between ground reaction forces, plantar pressures, and muscle electromyographic (EMG) activities and their interactions in the triple jump.

Methods

Participants

Four male (age 24 ± 2 years, height 185 ± 4 cm, body mass 76.7 ± 3.8 kg; mean $\pm s$) and three female (23 ± 3 years, 172 ± 2 cm, 63.6 ± 4.9 kg) national triple jumpers volunteered to participate in the study. Their mean personal best performances during competition were 13.25 ± 0.11 m and 15.75 ± 0.82 m for females and males, respectively, and time spent training for the group as a whole was 7 ± 3 years. All jumpers were fully informed of the procedures and possible risks of the experiment. They also provided written consent; the tests were a part of their training schedules as co-ordinated by their individual coaches.

Procedure and measurements

The measurements were made immediately after a competition season. The jumpers performed 3–6 jumps, the three longest of which were selected for analysis. Run-up speed during the last 5 m was measured with photocells (Digitest, Finland). During the hop, the step and the jump, two-dimensional ground reaction forces were measured using a force platform 13 m long (TR-test, Finland and Kistler, Switzerland; natural frequency ≥ 150 Hz and sampling frequency 1 kHz). As reference locomotion, the jumpers walked three times their preferred speed along a 30-m track, including the 13-m force platform.

A portable, in-shoe pressure data-acquisition system (Paromed-System®, GmBH, Germany; overall mass = 1.9 kg) was used to measure the plantar pressure distribution simultaneously with the bilateral electromyographic activity. The system has 16 piezoelectric microsensors embedded into water-filled hydrocells. Because of their design, the pressures measured by the sensors are associated with resultant forces and cannot be resolved into directional components. The insoles and EMG cables were connected to the Data Logger,

which was fixed by a belt to the jumper's back. The sampling frequency for the plantar pressure was 200 Hz, and for the EMG recordings it was 800 Hz (the bandwidth varied from 1 Hz to 120 kHz). The EMG was recorded with surface electrodes (Niko Medical Products, Type 4560, EU) from the gluteus maximus, vastus lateralis and gastrocnemius muscles of both legs. The electrodes were placed longitudinally over the muscle bellies between the centre of the innervation zone and the distal tendon of each muscle with an inter-electrode distance of 38 mm. The cross-talk between muscles was assumed to have minimal influence on the recorded signals because of the relatively large inter-electrode distance (Winter *et al.*, 1994).

The EMG and plantar pressure data were saved to an exchangeable memory card (SPRAM-PCMCIA type I) and further transferred to a Silicon Graphics workstation (Silicon Graphics, Inc., CA, USA) for processing, analysis and visualization. The data collection was initiated by remote control and was synchronized with the ground reaction force (Fig. 1). The signal transmitted by a light synchronization device was recorded in the Data Logger. The same signal was also sent telemetrically to another computer. During analysis, the triple jump recordings were divided into the hop, step and jump phases.

Data reduction

Contact times were divided into braking and push-off phases according to the direction of the horizontal ground reaction force (Mero and Komi, 1986). Maximal and average forces were analysed in two directions, as well as resultant forces and their directions. The EMG signals were full-wave rectified and the average
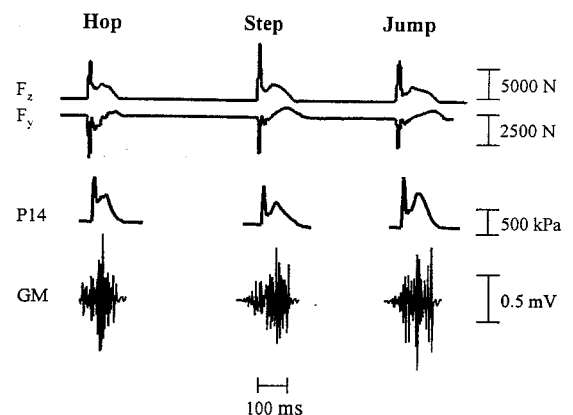

Fig. 1. Example of the two-dimensional ground reaction forces, plantar pressure distribution of the forefoot sensor (P14), and raw EMG signal of the gluteus maximus (GM) in the triple jump. The length of jump was 15.24 m.

EMG was computed for four phases: pre-activity (50–100 ms and 0–50 ms before touchdown), braking and push-off phases. The EMG amplitudes were then normalized to the average activities of five consecutive contacts that were recorded while walking at the jumper's preferred speed. Thus, the activities of walking were denoted as 100% for the four phases. Bilateral maximal plantar pressures of all sensors were analysed and contour curves drawn. All recorded and calculated signals were averaged intra-individually to obtain grand mean curves.

Statistical analysis

Multivariate analysis of variance for repeated measurements was used to test the main effects of repetitions and experimental conditions as well as all their combined effects on selected variables. This analysis revealed that the repetition had no statistically significant influence on any of the main variables. Therefore, all signals for each contact were averaged for each jumper. Stepwise multiple regression analysis was used to examine the relationships between variables. The mean and standard deviation (s) were calculated by conditions.

Results

The mean best performances were 14.32 ± 0.45 m (range 13.68–15.24 m) and 11.90 ± 0.28 m (range 11.37–12.39 m) for males and females, respectively. The grand mean was 13.25 ± 1.32 m, with a run-up speed of 8.65 ± 0.63 m·s^{-1}, which correlated highly ($r = 0.90$, $P < 0.001$) with triple jump performance. The contact times were different for each phase ($P < 0.001$), being 0.129 ± 0.007 s, 0.157 ± 0.009 s and 0.177 ± 0.010 s for the hop, the step and the jump, respectively.

The braking times were 0.079 ± 0.008 s, 0.087 ± 0.009 s and 0.113 ± 0.012 s, and the corresponding push-off times were 0.050 ± 0.006 s, 0.070 ± 0.003 s and 0.064 ± 0.007 s, for the hop, the step and the jump, respectively.

The vertical and horizontal ground reaction forces were largest during the step. For all contacts, the ground reaction forces were greater in the braking phases than in the push-off phases (Table 1). In the braking phase of the hop, the step and the jump, the maximal ground reaction force was 11.3 ± 3.6, 15.2 ± 3.3 and 12.9 ± 3.1 times body weight in the vertical direction and 4.8 ± 1.4, 7.0 ± 3.9 and 6.2 ± 1.1 times body weight in the horizontal direction, respectively. To study the ground reaction forces affecting the final distance in the triple jump, the force curves of the hop, step and jump were averaged. Stepwise multiple regression revealed that the maximal vertical force in the braking phase and the maximal horizontal force in the push-off phase were the best ground reaction forces for predicting the final distance in the triple jump (58.9% and 27.1%, respectively).

The highest peak pressures were recorded under the heel and forefoot areas, and the lowest pressures under the midfoot, in the triple jump. In several cases, the heel pressures (sensors 1 and 2; see Fig. 2) were so high that the signals exceeded the range of the transducers. The observed peak pressures were more than four times greater in the triple jump than in normal walking (Fig. 2). In the triple jump, the heel and forefoot sensors responded at the same time, implying that the sole of the foot touched flat to the ground. A comparison of the maximal pressures revealed that the rearfoot area and big toe region were significantly different ($P < 0.05$) between the hop, the step and the jump, with the lowest values being recorded during the hop. The pressure distribution patterns differed considerably over time as shown by the contour curves drawn 20 ms after touchdown, during midstance and 20 ms before take-off (Fig. 3) during all three phases of the triple jump.

Table 1. Maximal vertical (F_z), horizontal (F_y) and average resultant (F_r) ground reaction forces and their directions (mean $\pm$ s), with the direction denoting the angle of the average resultant force vector in the two phases

	Hop	Step	Jump
Max. braking F_z (N)	7945 ± 2985	10624 ± 2872	9056 ± 2639
Max. braking F_y (N)	3347 ± 1207	4973 ± 2967	4336 ± 932
Max. push-off F_z (N)	2535 ± 519	2680 ± 470	2491 ± 633
Max. push-off F_y (N)	440 ± 157	486 ± 86	358 ± 116
Av. braking F_r- BW (N)	2475 ± 384	3052 ± 459	2649 ± 560
Braking angle (°)	67.7 ± 2.1	71.0 ± 5.4	69.5 ± 3.3
Av. push-off F_r-BW (N)	1125 ± 259	1239 ± 203	1155 ± 405
Push-off angle (°)	76.1 ± 3.0	74.9 ± 1.3	78.6 ± 3.3

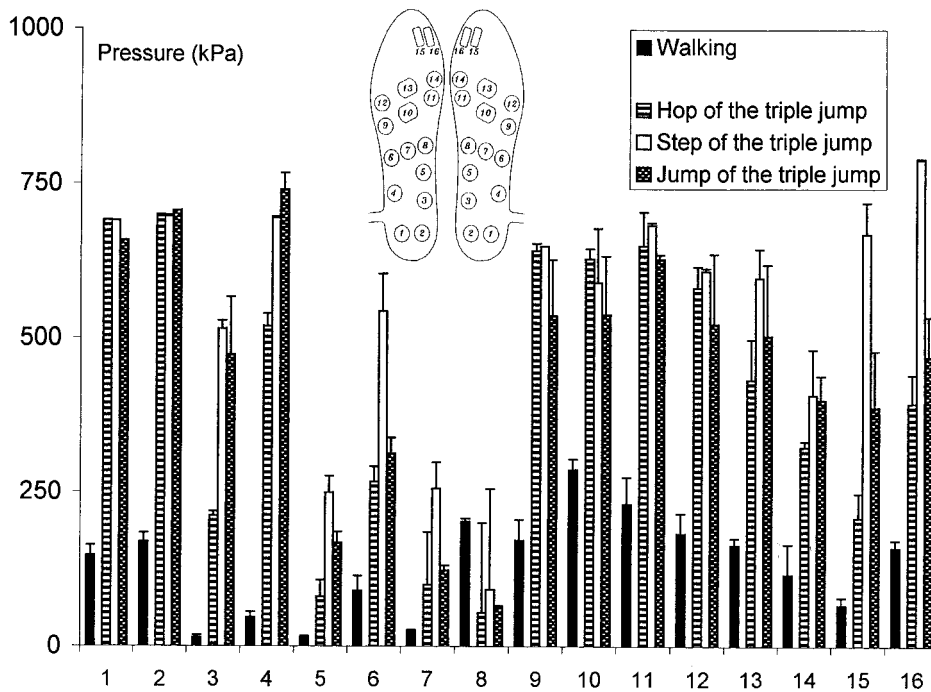*Abbreviation*: BW = body weight.

Fig. 2. Example of the peak pressures of the various sensors for one male jumper measured during the hop, step and jump phases of the triple jump and during walking. The missing standard deviation bars indicate that the signals exceeded the range of the sensors.
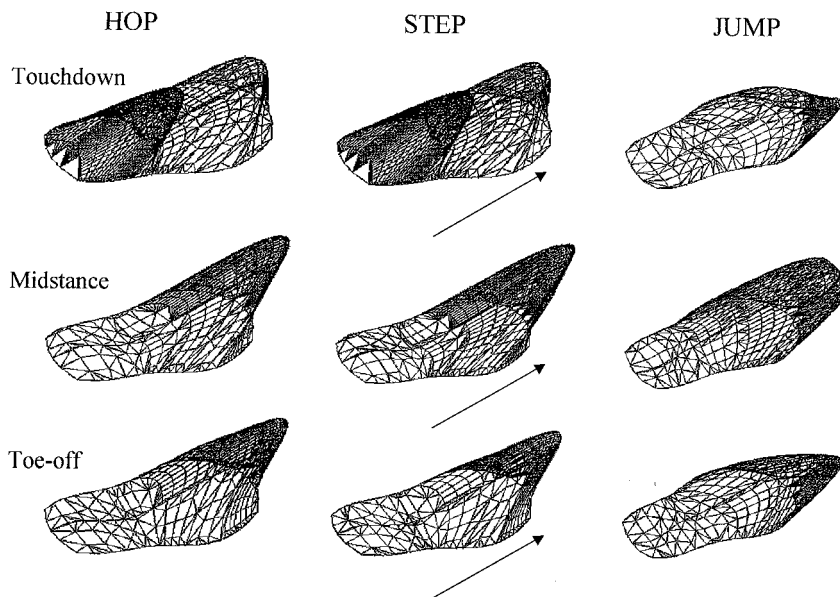

Fig. 3. The contour curves of the plantar pressures measured 20 ms after touch-down, in the middle of the stance phase and 20 ms before toe-off. The arrows indicate jumping direction.

It must be noted that these points do not represent the peak pressure points of each sensor. Importantly, however, the peak pressures under the lateral forefoot (sensors 6, 9 and 12) correlated positively ($P < 0.001$) with the length of the triple jump ($r = 0.71$, $r = 0.87$, $r = 0.90$, respectively) (Fig. 4).

Figure 5 shows bilateral muscle activity patterns during the hop, step and jump. In individual analyses, all these phases demonstrated high pre-activity and braking activity of the leg extensor muscles. The mean EMG values of the vastus lateralis muscle were greater ($P < 0.001$) during the braking phase than push-off

phase (Fig. 6). However, no clear quantitative phase (hop, step and jump) differences were observed in any of the measured EMG patterns.

Discussion

The results of the present study not only confirm that a triple jumper must be able to tolerate very high ground reaction forces (Ramey and Williams, 1985; Jin, 1989), but provide detailed and important information about their production. To obtain a reference of loading magnitudes in the triple jump, the maximal ground reaction forces and peak plantar pressures were related to body weight during walking. The maximal peak vertical forces during impact were almost ten times higher and the peak pressures four times higher in the triple jump than during walking. However, the average vertical force in the triple jump was also about four times that recorded during walking. This suggests that the sampling frequency used for pressure sensors (200 Hz) was not fast enough to record the true peak values.
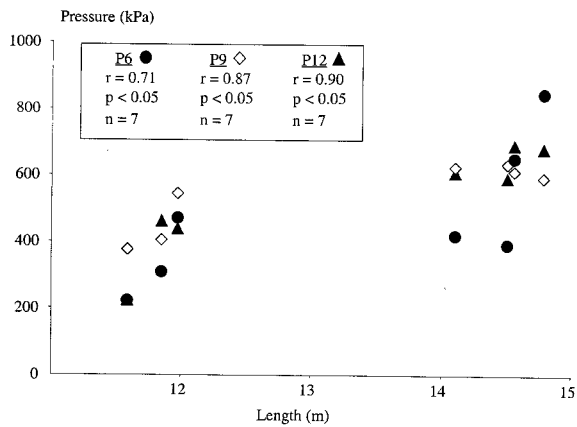

Fig. 4. Relationship between the length of the triple jump and the peak plantar pressures of the lateral forefoot (sensors 6, 9 and 12) measured during the hop, step and jump.
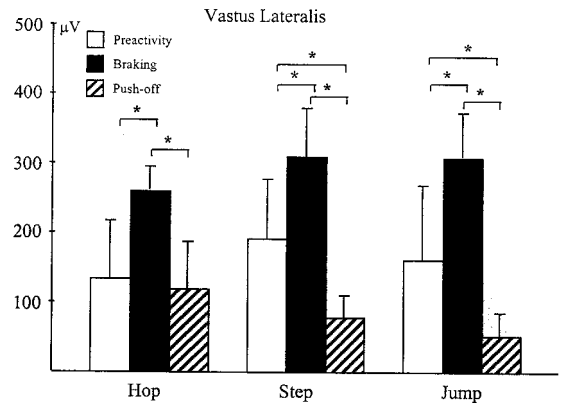

Fig. 6. Mean (± s) average EMG of the vastus lateralis muscle in the pre-activity (☐), braking (■) and push-off (▨) phases. Asterisks denote differences between hop, step and jump ($P > 0.05$).
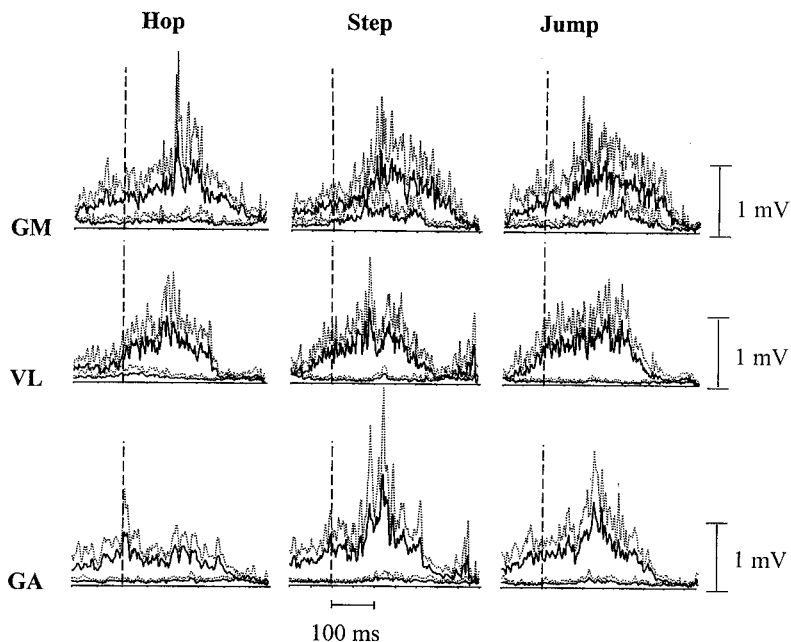

Fig. 5. Grand mean (± s) curves of the muscle activity patterns of the gluteus maximus (GM), vastus lateralis (VL) and gastrocnemius (GA) muscles bilaterally. The vertical dashed lines indicate the onset of contact.

Surprisingly, however, the recorded sensor pressures were similar to those reported for another high impact load sport, javelin throwing (Bartlett *et al.*, 1995). Thus, the peak plantar pressures and the peak vertical ground reaction forces cannot be used to identify the impact loading in the same way.

The individual scatters of the points in the relationship between pressures under the lateral side of the forefoot and the length of the triple jump (Fig. 4) could be due to differences between the sexes, because the female jumpers were all in the lower end of the length axis. To investigate this possibility, 10 additional jumps by one experienced male jumper were recorded; he performed these jumps with a range of jump lengths of 10.00–13.92 m. These results are presented in Fig. 7 and support the close relationship between the length of the jump and the peak plantar pressures of the lateral side of the forefoot. This intra-individual comparison does not confirm dependence on sex in the obtained relationships. Our peak values both for the heel and the lateral side of the forefoot are similar to the 700 kPa reported by Nicol (1977) for the heel. However, these peak values do not necessarily describe the weight-bearing models of the foot during locomotion. Therefore, the pressure distribution expressed at certain instants or drawn as contour curves during the entire contact phase may be more relevant to characterize the foot loads during the triple jump (Fig. 3).

The resultant forces and their directions in the braking phases, together with gradually lengthened contact times, suggest further that the horizontal speed decreases from the hop to the jump (Table 1). This latter finding is in line with previous studies (e.g. Fukashiro *et al.*, 1981), in that the longest stance time was observed in the jump phase. However, to maintain high horizontal speed throughout the triple jump, the inclination of the braking angle of the average resultant force should be closer to 90°. This means that the muscle actions and their timing need to be well coordinated.

The high impact loading demonstrated in the present study requires well-developed pre-landing motor control similar to that for other high-impact, stretch–shortening cycle exercise (Horita *et al.*, 1999). This can be seen as high and fast EMG development just before the touch-down and during the braking phase (Fig. 6). The high pre-landing and braking activity of the leg extensor muscles might prevent unnecessary yielding of the jumper during the braking phase, resulting in a better performance, as demonstrated by Fig. 8. Pre-activation appears further to be a preparatory requirement both for the enhancement of EMG activity during the braking phase, and for the timing of muscular action with respect to ground contact (Komi *et al.*, 1987). Centrally programmed pre-landing activity
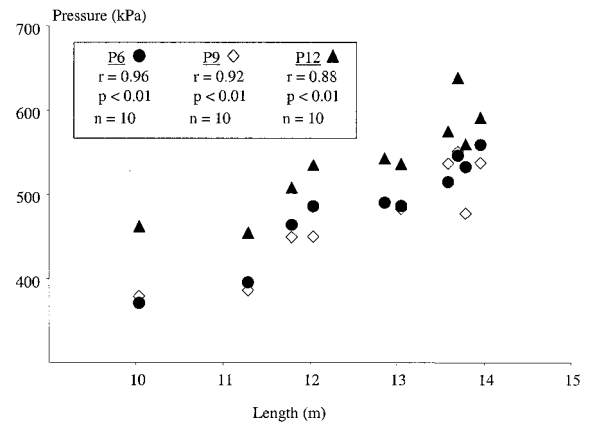

Fig. 7. Relationship between the length of the triple jump and the peak plantar pressures of the lateral forefoot (sensors 6, 9 and 12) of one experienced male jumper measured during the hop, step and jump.
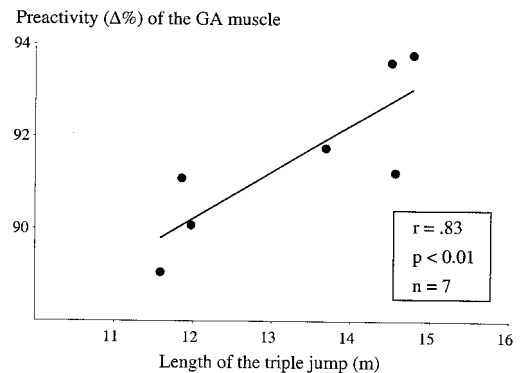

Fig. 8. Relationship between the length of the triple jump and the pre-activity of the gastrocnemius (GA) muscle recorded 50 ms before touch-down during the hop, step and jump. The EMG activity was normalized to the average EMG amplitudes of the five consecutive gait cycles of the jumper's preferred walking speed.

(Melvill-Jones and Watt, 1971) also appears to be important for regulating landing stiffness (e.g. Gollhofer and Kyröläinen, 1991) and for compensating local muscular failure (e.g. Horita *et al.*, 1996). Furthermore, pre-activity is assumed to increase the sensitivity of the muscle spindle through enhanced alpha–gamma co-activation, thus potentiating stretch reflexes (Gottlieb *et al.*, 1981) and enhancing tendomuscular stiffness and performance (Nichols and Houk, 1976; Gollhofer *et al.*, 1984; Kyröläinen *et al.*, 1989).

Another explanation for unnecessary yielding of the jumper might be the ineffective action of the hip extensor muscles. The role of the gluteus maximus is to extend the hip joint and to prevent its unnecessary displacement downwards. Among athletes such as in

the present study, lowering of the centre of mass of the whole body owing to decreased activity of the gluteus maximus may be apparent. As a consequence of yielding in the hip joint during the braking phase, greater displacements of the knee and ankle joints could be observed. To prevent this unnecessary movement, high muscle activity is required in the braking phase for both the knee extensors and plantar flexors. In the present study, this was seen as high braking activity of the vastus lateralis compared with the respective push-off phase, especially in the jump stage.

Failure of the neuromuscular protective mechanisms – for example, in the case of inappropriate coordination – has been hypothesized to be a critical factor underlying the occurrence of musculoskeletal injuries in the triple jump (Kannus and Natri, 1997). Training with the high strain and high peak forces used by triple jumpers has been shown to increase bone formation, when compared to training with many low peak force repetitions (Heinonen *et al.*, 1995, 1998).

In conclusion, we have clarified the mechanical loadings and the role of neuromuscular function in the triple jump. The largest ground reaction forces were observed in the step. Furthermore, the maximal vertical force in the braking phase and the maximal horizontal force in the push-off phase are the best ground reaction forces for predicting the final distance in the triple jump. The plantar pressure of the lateral side of the forefoot was highly related to the length of the jump, and the highest peak pressures were obtained under the heel and forefoot. The EMG results suggest that the mechanical loading places high demands on the neuromuscular system, as characterized by the high rate of activation in the pre-activity phase followed by high eccentric activity of the leg extensor muscles.

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