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Three-dimensional motion analysis of the forefoot, midfoot, and rearfoot for various directions of motion after landing

Hiroyuki Furukawa, RPT, MSc, Satoshi Okubo, RPT, Kenji Fujita, MD, PhD, Tomoaki Shimada, RPT, PhD.

Abstract
Adequate motion of the lower legs during landing is important from the viewpoint of injury prevention and improvement of performance. Although many previous studies on this subject have focused on the knee and hip joint, few have investigated detailed motion of the foot during and after landing. Considering that only the foot contacts with the ground at landing, the motion of the foot might strongly affect subsequent motion in the knee and hip joints. Therefore, the purpose of this study was to analyze the detailed motion of the foot during and after landing and determine adequate motion of the foot after landing. The subjects were 18 healthy college students. The four tasks were 1) vertical jump, 2) forward dash, 3) side step, and 4) crossover step, which were performed immediately after one leg landing following stepping off a 30 cm stand. A difference was seen in the 1-5 angle and the angles of pronation and supination in each section of the foot during the side step and crossover step. The movement required in the forefoot after landing and while subsequently stabilizing posture to continue movement differs depending on the direction of motion chosen. It is suggested that treatment focusing on forefoot pronation and supination mobility and foot muscle strength to fix forefoot movement is necessary for rehabilitating the feet of athletes.

Key words:
3-dimensional motion analysis, forefoot, midfoot, rearfoot, landing

Introduction

In sports, landing is considered to be one of the causes of foot and lower leg injuries(1-7), which we frequently encounter clinically. During sporting activities, where conditions change from moment to moment, movement is demanded in a variety of directions after landing. According to Yu et al., an adequate landing is necessary from the viewpoint of both injury prevention and performance(8). Many previous studies of landing have focused on the knee joint and hip joint(9-11), and analyses of the foot and ankle have been limited to the ankle(12). Considering that only the foot contacts with the ground at landing, the motion of the foot might strongly affect subsequent motion in the knee and hip joints. There is no study on the detailed motion of the foot after landing.

In regard to detailed studies of the foot, Leardini et al. used a three-dimensional motion analysis system to analyze walking motion, dividing the foot into the three sections of the forefoot, midfoot, and rearfoot(13-14). According to these studies, analysis of the foot using a three-dimensional motion analysis system is noninvasive and exhibits repeatability of results and appropriateness. Although a number of

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other researchers have used three-dimensional motion analysis systems to perform a detailed analysis of the foot\(^{17-25}\), most of these have studied walking; few have analyzed motion simulating sport actions\(^{27-29}\).

From these backgrounds, this study aims to perform a detailed analysis of the motions of the foot during various directions of motion after landing, by using a three-dimensional motion analysis system, and furthermore, to elucidate the characteristics of foot motion due to differences in action in order to aid future injury prevention.

**Method**

**Subjects**

The subjects were 18 (11 men, 7 women) healthy college students with no history of orthopedic surgery or neurologic disorder in the leg and foot to be measured. Their physical characteristics are shown in Table 1. The dominant foot, which was determined using the standard of Schmitz et al.\(^{(9)}\), was used for measurement. All measurements were taken barefooted. Written informed consent to participate was obtained from all subjects after they had received explanations of the main purpose of the study, the measurements to be taken, and any potential dangers associated with the measurement. The study protocol was approved by the Ethics Committee of Kobe University Graduate School of Health Sciences.

**Instruments and protocols**

All measurements were performed using the three-dimensional motion analysis system MAC 3D System (Motion Analysis Corporation, Santa Rosa, USA) and a ground reaction force measurement device (Kistler Holding AG, Winterthur, Switzerland), with the sampling frequency set at 200 Hz. Ten infrared cameras were set with a region in space of dimensions of 3.5m length, 2m width, and 3m height in which measurements could be taken, and the tasks were performed in this region (Figure 1). The locations at which the reflective markers were attached were based on the method of Leardini et al.\(^{13}\) and reflective markers (10 mm diameter) were attached to the knee joint on the measurement side, the lower leg, the ankle joint, and the foot, at the following 17 locations: 1) medial knee joint space (MK), 2) lateral knee joint space (LK), 3) fibular shaft center, 4) medial malleolus of the ankle (MA), 5) lateral

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**Fig 1. Test room layout**

Ten infrared cameras were installed on the ceiling, and the measurable region, including four ground reaction force measurement devices, was 3.5m long, 2m wide, and 3m high.

**Fig 2. Placement of reflective markers**

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maellolus of the ankle (LA), 6) calcaneal tuberosity, 7) sustentaculum tali (ST), 8) peroneal tuberosity (PT), 9) navicular tuberosity, 10) base of the 1\textsuperscript{st} metatarsal (1MB), 11) head of the 1\textsuperscript{st} metatarsal (1MH), 12) base of the 2\textsuperscript{nd} metatarsal, 13) head of the 2\textsuperscript{nd} metatarsal, 14) base of the 5\textsuperscript{th} metatarsal (5MB), 15) head of the 5\textsuperscript{th} metatarsal (5MH), 16) head of the 1\textsuperscript{st} proximal phalanx, and 17) head of the 5\textsuperscript{th} proximal phalanx (Figure 2).

In regard to the order of measurement, the posture while standing still was measured first. Next, after stepping with one leg off a 30 cm stand and landing, one of four motions was performed: 1) vertical jump, 2) forward dash, 3) side step (stepping from the side of measurement to the opposite side), 4) crossover step (stepping toward the measurement side). The landing involved keeping one leg standing on the 30 cm stand, and performing a landing on the ground reaction force measurement device. For this motion, the subjects were instructed not to propel themselves much upward from the stand, and were not given any other special instructions. The subjects were also instructed to perform the vertical jump as quickly and as high as possible, and after changing direction to perform the forward dash, side step, and crossover step, to start running in the same direction. Each subject performed each task twice after practicing them thoroughly.

Data analysis
A foot model was produced from the measured marker positions in the following manner. Using the marker positions, virtual points were calculated: intermediate knee (midpoint between MK and LK), intermediate ankle (midpoint between MA and LA), intermediate rearfoot (midpoint between ST and PT), intermediate midfoot (midpoint between 1MB and 5MB), and intermediate forefoot (midpoint between 1MH and 5MH). Four segments were created: lower leg (segment connecting intermediate knee and intermediate ankle), rearfoot (segment connecting calcaneal tuberosity and intermediate rearfoot), midfoot (segment connecting intermediate rearfoot and intermediate midfoot), and forefoot (segment connecting intermediate midfoot and intermediate forefoot). Each foot segment was defined such that around the X-axis (the axis facing from the inner to the outer side) was plantar flexion and dorsiflexion, around the Y-axis (the axis facing from the calcaneus to the toes) was pronation and supination, and around the Z-axis (the axis perpendicular to the point of intersection of the X- and Y-axes) was abduction and adduction. The value of each foot segment is expressed as the angle relative to neighboring proximal segments, where the value while standing still is expressed as 0°.

The items for analysis were the angle from ankle plantar flexion to dorsal flexion (the angle formed by intermediate knee-intermediate ankle-intermediate forefoot); the pronation and supination angles of the rearfoot, midfoot, and forefoot; the angle between the first metatarsal bone and the fifth metatarsal bone

| Table 2. Average values for each analysis item while standing |
|-----------------|-----------------|-----------------|-----------------|
| Plantar-dorsiflexion angle of ankle | 1-5 angle | Transverse arch angle | Rearfoot pronation-supination angle* | Midfoot pronation-supination angle* | Forefoot pronation-supination angle* |
| 102.50±1.11 | 24.07±7.38 | 82.19±4.38 | 0.07±0.04 | -0.09±0.05 | 0.08±0.14 |

*Supination is expressed as a positive value, and pronation as a negative value.
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(hereafter: 1-5 angle); the midfoot transverse arch angle (the angle formed by navicular tuberosity - base of the 2nd metatarsal - 5MB; hereafter: transverse arch angle); and the perpendicular component of the ground reaction force measurement device (hereafter: ground reaction force component) (Figure 3). During landing, the moment of touching the ground and the moment of leaving the ground again were identified using the values from the ground reaction force measurement device, and all the data were normalized such that the time from touching the ground to leaving it again was 100%.

Results

The mean value and standard deviation for each item for analysis while standing still are shown in Table 2. While standing still, both feet were on the ground, and the phase where the loads on the left and right sides were virtually the same was taken as the representative value for each subject. The results for each of the tasks are as follows (Figures 4-7).

![Graphs of Plantar-dorsiflexion angle of ankle, 1-5 angle, Transverse arch angle, Rearfoot pronation-supination angle, Midfoot pronation-supination angle, Forefoot pronation-supination angle, and Rearfoot Ground reaction force perpendicular component.]

Fig 4. Average values and standard deviations for vertical jump for: plantar-dorsiflexion angle of ankle, 1-5 angle, transverse arch angle, rearfoot pronation-supination angle, midfoot pronation-supination angle, forefoot pronation-supination angle and ground reaction force perpendicular component Rearfoot. A larger plantar-dorsiflexion angle of the ankle indicates plantar flexion, and a smaller value indicates dorsiflexion. For the pronation-supination angle for each portion of the foot, a positive value indicates supination, and a negative value pronation.
Vertical jump (Figure 4)

The ankle was plantar flexed at the moment of touching the ground (36.4±3.43°), and was gently dorsiflexed from the 20% to about the 80% of the ground contact period (max dorsiflexion; 18.2±4.7 5°) before plantar flexing again and leaving the ground. The 1-5 angle had a large value during the initial and final parts of the ground contact period (32.8±7.63° and 29.4±9.72°, respectively) when only the forefoot was touching the ground, and was around 20° (from 21.4±8.04° to 23.2±8.37°) during the middle portion when the entire foot was touching the ground. The transverse arch angle was large during the initial and final parts of the ground contact period (86.0±3.77° and 84.9±4.85°, respectively) when the midfoot was not contacting the ground, and was around 82° (from 80.7±4.02° to 83.0±4.08°) while the midfoot was contacting the ground. Then, after pronating around 13° (from 6.6±4.28° supinated to 6.7±3.95° pronated) in conjunction with an increase in ground reaction force component from a supinated position at time of contact, the rearfoot supinated again as it left the ground. The midfoot maintained slight pronation (mean 2.1±0.51°) with respect to the rearfoot during this entire period. The forefoot was pronated with respect to the midfoot during the initial contact period, but was slightly supinated during the middle period, returning to a pronated state in the final period. The change in angle between the two states was 5.4° (from 1.4±1.72° supinated to 4.0±2.61° pronated). The ground reaction force component peaked at the 15% of the ground contact period and decreased thereafter until leaving the ground. The peak value was 1782.1±341.38 Nm.

Fig 5. Average values and standard deviations for forward push. : A larger plantar-dorsiflexion angle of the ankle indicates plantar flexion, and a smaller value indicates dorsiflexion. For the pronation-supination angle for each portion of the foot, a positive value indicates supination, and a negative value pronation.
Fig 6. Average values and standard deviations for side step. A larger plantar-dorsiflexion angle of the ankle indicates plantar flexion, and a smaller value indicates dorsiflexion. For the pronation-supination angle for each portion of the foot, a positive value indicates supination, and a negative value pronation.

**Forward dash (Figure 5)**

The ankle was plantar flexed when touching the ground (28.1 ± 4.04°), and increasingly dorsiflexed into the middle period, reaching maximum dorsiflexion (34.1 ± 4.27°) at the 50% of the ground contact period. Of the four tasks, this was the largest angle of dorsiflexion. The 1-5 angle, transverse arch angle, and rearfoot pronation-supination angle were very similar to those of the vertical jump. During the initial period and the final 10% of the ground contact period, the midfoot was slightly pronated with respect to the rearfoot (2.2 ± 2.32° and 2.6 ± 3.07°, respectively), but was mildly supinated the rest of the time. The change in angle between the two states was 5.7° (from 3.2 ± 2.59° supinated to 2.6 ± 3.07° pronated). The forefoot and ground reaction force component were very similar to those of the vertical jump. The peak ground reaction force component value was 1552.4 ± 305.42 Nm.

**Side step (Figure 6)**

The plantar-dorsiflexion angle of the ankle was similar to that in the vertical jump. The change in 1-5 angle was similar to that in the aforementioned second task, however the angle was smaller, having a minimum of 10.5 ± 5.49°. The transverse arch angle was similar to that in the vertical jump and forward dash. The rearfoot touched the ground in a supinated position. Although it then pronated, once it reached a similar value to that of standing still, it maintained that angle, and began supination again at around 50% of the ground contact period, continuing until leaving the ground again. The midfoot and
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Fig 7. Average values and standard deviations for crossover step. A larger plantar-dorsiflexion angle of the ankle indicates plantar flexion, and a smaller value indicates dorsiflexion. For the pronation-supination angle for each portion of the foot, a positive value indicates supination, and a negative value pronation.

forefoot were supinated with respect to the rearfoot for almost the entire time, and both reached a peak of $8.7\pm2.53^\circ$ and $8.5\pm1.80^\circ$ at 80% of the ground contact period. The ground reaction force component was similar to the other tasks, with a peak of $1828.9\pm627.15$ Nm.

Crossover step (Figure 7)
The degree of ankle plantar-dorsiflexion was similar to those of the vertical jump and the side step. After increasing during the initial ground contact period where the forefoot was contacting the ground, the 1-5 angle decreased until around 20% of the ground contact period, after which it increased again, peaking at 75% of the ground contact period with a value of $41.7\pm9.93^\circ$. The transverse arch angle was similar to that of all tasks. The rearfoot pronated from a supinated position during ground contact, and reached the lowest angle of the four tasks of $13.6\pm5.05^\circ$ (at 36% of the ground contact period). Afterwards, it supinated, and reached an angle similar to those of the other tasks at the point of separation from the ground. The midfoot and forefoot were pronated with respect to the rearfoot for the entire time in a different manner from the other tasks. The ground reaction force component was similar to the other tasks, with a peak of $1437.9\pm294.25$ Nm.
Discussion

Using a three-dimensional motion analysis system, the differences in foot motion based on differences in motion after a one -foot landing were comparatively examined. In general, when performing three-dimensional motion analysis, problems arise with how to approximate the foot (which has many bones) as a rigid body, and the fact that errors arise in the motion of the markers attached to the body with respect to the actual motions of the bones, as they are attached to the skin and over soft tissue (16-18). However, it is reported that markers attached to landmarks on the foot produce less error than those attached to the skin of the lower or upper leg (16), and are therefore useful for taking measurements once the limitations of this measurement method are understood.

In the present results, when using the values for standing still as a standard, the plantar-dorsiflexion angle of the ankle joint was a plantar flexed angle of $30^\circ$ when the forefoot contacted the ground, which changed to a dorsiflexion angle of close to $20^\circ$ when the heel contacted the ground, before returning to plantar flexion until leaving the ground again (Figure 4, 6, and 7). The degree of dorsiflexion during the forward dash exceeded that of the other three tasks, and exceeded $30^\circ$ dorsiflexion (Figure 5). This was considered to occur to shift the center of weight forward smoothly by increasing dorsiflexion of the ankle joint, as it was necessary to shift the center of weight forward after landing.

The 1-5 angle was essentially the same between the forward dash and the vertical jump performed after a one -foot landing. An increase in this angle was noted at the time of landing of the forefoot, which settled into a fixed value of around $20^\circ$ from the middle of the ground contact period (Figures 4 - 7). As also reported by Leardini et al. (13), the angle formed by the first toe and the fifth toe with respect to the second toe opens up to toe-off when walking, which can be considered a similar result to that of the present study. Although the values for the middle of the ground contact period were slightly lower than those of standing still, this is thought to be because the 5MB marker was spread out, as the load was higher due to the one -foot landing (Figures 4 - 7). Furthermore, a difference in pattern was noted between the side step and crossover step and the vertical jump and forward dash. In the side step, it was thought that as the load moved to the first toe, the 5MH marker was pushed inward (Figure 6), and conversely in the crossover step, as the load moved to the fifth toe, the 5MH marker was pushed outward. (Figure 7) Essentially, it was thought that in the forefoot, the movement changed as a result of the motion that arose from the twist in the sidestep and the crossover step.

The transverse arch angle was similar across the four tasks. During the middle portion of the ground contact period in which the load is centered on the midfoot, the angle was nearly identical to that of standing still, and the angle was greater during the initial and final periods when the load is centered on the forefoot (Figures 4 - 7). This occurred regardless of differences in load and motion, and can be considered to occur in order to stiffen the midfoot when load is applied, and can be thought of as supporting the studies of Carson et al. (17) and Leardini et al. (13) which considered it a transmission mechanism for the forces connecting the midfoot to the forefoot and rearfoot.

In terms of rearfoot pronation and supination, although a nearly fixed angle of supination was seen across the tasks at the moment of ground contact, a difference in angle of pronation was noted during the middle of the ground contact period during the side step and the crossover step. Pronation of the rearfoot is also seen during ambulation, which is said to have the role of a buffering action. Although the pronation of the rearfoot during ground contact in the present study's tasks was also considered to ease the shock of landing, it was thought that the incline of the lower leg in the direction of motion in order to switch to the next movement manifested in a difference in angle. This case was considered to be the same for the midfoot and the forefoot. During the side step, the midfoot was supinated with
respect to the rearfoot, and the forefoot was supinated with respect to the midfoot (Figure 6) and during the crossover step, the position was continuously pronated (Figure 7). This was thought to indicate that in a series of stepping actions, the foot rotates sequentially in the direction of motion from the rearfoot, and combined with the side step and crossover step, it is suggested that rotational mobility of up to 20° is necessary in the midfoot and forefoot.

In this study, the movements of various portions of the foot during a variety of motions were clarified. In particular, the results suggest the need for rehabilitation which takes into account the differences in movement pattern of the midfoot and forefoot when moving sideways (Figures 6 and 7). Specifically, there is a need to maintain midfoot and forefoot pronation and supination mobility because the midfoot and forefoot are required to rotate 20°, and to strengthen the foot muscles which stabilize the midfoot and forefoot in order to move while rotational stress is applied.

As this study used a three-dimensional motion analysis system with healthy subjects, these results cannot necessarily be generalized to patients with foot disorders. In the future, studies involving patients with foot disorders as subjects and multifaceted studies which combine other measurement methods aside from three-dimensional motion analysis are warranted.

References

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