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ORIGINAL

# Effects of Landing Foot Orientations on Biomechanics of Knee Joint in Single-legged Landing

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**Objective:** This study aimed to investigate the influence of landing foot orientations on biomechanics of knee joint in order to identify vulnerable positions to non-contact knee injuries during single-legged landing.

**Method:** Seventeen men (age: 20.5±1.1 years, height: 175.2±6.4 cm, weight: 68.8±5.8 kg) performed single-leg drop landings repeatedly with three different landing foot orientations. They were defined as toe-in (TI) 30° adduction, neutral (N, neutral), and toe-out (TO) 30° abduction positions.

**Results:** The downward phase time of TI was significantly shorter than those of N and TO. The flexion and valgus angle of N was greater than those of TI and TO at the moment of foot contact. At the instance of maximum knee flexion, N showed the largest flexion angle, and TO position had the largest varus and external rotation angles. Regarding ground reaction force (GRF) at the moment of foot contact, TO showed the forward GRF, while others showed the backward GRF. TI indicated significantly larger mediolateral GRF than others. As for the maximum knee joint force and joint moment, the main effect of different foot positions was not significant.

**Conclusion:** TI and TO might be vulnerable positions to knee injuries because both conditions might induce combined loadings to knee joint. TI had the highest mediolateral GRF with a shortest foot contact time, and TO had induced a large external rotation angle during downward phase and the peak forward GRF at the moment of foot contact. Conclusively, N is the preferred landing foot orientation to prevent non-contact knee injuries.

**Keywords:** Knee joint, Single-legged landing, Foot orientation, Joint moment

## INTRODUCTION

With increasing participation in various leisure and sports activities for the purpose of health improvement, the occurrence of sports injuries are rising proportionally. With respect to body parts involved in injuries during sport activities, injuries in the lower extremities account for a two-third of all injuries (Hootman, Dick, & Agel, 2007). Injuries in the lower extremities are often non-contact injuries caused by jumping, landing, accelerating, decelerating, and rotating motions during sports such as basketball, soccer, volleyball, and gymnastics. In particular, landing motion, is an unavoidable motion in most sports activities and is closely associated with sports injuries (Boden, Dean, Feagin, & Garrret, 2000; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001; Olsen, Myblebust, Engebrestsen, & Bahr, 2004; Woods, Hawkins, Hulse, & Hodson, 2002; Yeow, Lee, & Goh, 2010; Zhang, Bates, & Dufek, 2000).

A landing motion can be divided into double- and single-legged landings. Since many sports such as basketball, volleyball, gymnastics, and handball more frequently require single-legged landings, the frequency of injuries in single-legged landings tends to be higher than that in double-legged landings (Mountcastle, Posner, Kragh, & Taylor, 2007; Orishimo, Kremenic, Pappas, Hagins, & Liederbach, 2009; Powell & Barber-Foss, 2000) are of common causes of injury is attributed to improper landing postures after jumping (Boden et al., 2000; Griffin, Agel, & Albohm, 2000; Noyes, Mooar, & Neimann, 1983; Powell et al., 2000; Shimokochi & Shultz, 2008). Improper landing posture can easily results in injuries in the knees or ankles. According to a study on shock absorption during landing, the energy absorption rate from the ankle plantar flexor, knee extensor, and hip extensor muscles was 22%, 41%, and 38% in men, respectively, and 40%, 41%, and 19% in women, respectively. Based on these study results, the knees is considered to play an important role in absorbing shock during landing in both men and women (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Devita & Skelly, 1992; McNitt-Gray, 1991; Schot, Bates, & Dufek, 1994; Zhang et al., 2000).

The knees can primarily generate or absorb energy on the sagittal plane as a result of flexion and extension motions. Improper landing posture tends to induce additional loadings on knees simultaneously to other anatomical planes besides the sagittal. In particular, combining loading with simultaneous internal or external rotation moment and excessive knee valgus during landing can be very dangerous, and thus, proper posture and shock absorption strategies during landing are necessary (Agel, Evans, Dick, Putukian, & Marshall, 2007; Agel, Palmieri-Smith, Dick, Wojtys, & Marshall, 2007; Dufek & Bates 1990). Previous studies have emphasized the importance of landing posture by allowing changes in the landing orientation of the body, changes in arm position during landing, and gender-based difference in landing height. Most of these studies identified the mechanism involved in shock absorption or reported simple differences between different populations and genders. However, those studies were based on execution while the feet and body maintained a neutral position (Decker et al., 2003; Kernozek, Torry, Hoof, Cowley, & Tanner, 2005; Kim & Youm, 2012; McNitt-Gray, 1993; Nigg, Bahlsen, Luethi, & Stokes, 1987; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004; Scott & Winter, 1990).

Combined loading generated in the knees is considered to be caused by not being able to maintain the neutral position of the feet and body. This condition could apply different shocks to the inner and outer sides of the knees due to changes in the foot orientation during landing. In other words, changes in foot landing posture can cause injuries through combined loadings such as simultaneous loading of internal/external rotation moment and/or varus/valgus moment on the knees (Koga et al., 2010; Shimokochi et al., 2008; Shin, Chaidhari, & Andriacchi, 2011). Injury caused by combined loadings is known to most commonly occur within 50 ms immediately after ground contact when knee flexion angle is small (Shin, Chaudhari, & Andriacchi, 2009). However, studies on changes in landing foot orientation are still lacking.

To date, the effects of foot orientation on knee loading have been reported only in studies related to gait. When comparing toe-out and toe-in due to inward deviation of the legs during gait, toe-out gait caused the center of pressure (COP) to shift laterally during initial stance phase, resulting in reducing the adduction moment applied on the knees. This can be considered as gait pattern adaption that can help reduce knee pain and loadings on knees (Jung, 2004; Wang, Kuo, Andriacchi, & Galante, 1990; Go, Hong, Lee, & An, 2013). However, since similar studies for landing motion were not yet reported, information on loading on knee joints according to landing foot orientations is unavailable.

Accordingly, the present study aimed to investigate the effects of landing foot orientation on the kinematic and kinetic variables of the knees during single-legged landings on the ground from a certain height (35 cm) and to identify foot orientations that are vulnerable to knee injury. The study also aimed to use the findings in providing athletes with information about proper landing posture after jumping.

## METHODS

### 1. Participants

The participants in the study consisted of seventeen male adults (mean age: 20.5±1.1 years, height: 175.2±6.4 cm, and body weight: 68.8±5.8 kg) who did not have any musculoskeletal disease in the lower extremities in last one year. The experiment was conducted after explaining the objective and procedures of the study to the participants and obtaining their informed consent.

### 2. Experimental tools

A total of eight high-speed infra-red cameras (Eagle®, Motion Analysis Cooperation, USA) with sampling rate of 120 Hz were used to capture landing motions and manufacturer-supplied software, Cortex 4.1® (Motion Analysis Cooperation, USA), was used for data processing. A force platform (Type 9281E, Kistler, Amherst, NY, USA) with a sampling rate of 1,200 Hz was used to measure the ground reaction force (GRF) generated when landing. For motion data acquisition, 19-mm reflective markers were affixed on major anatomical landmarks with double-sided tape (Figure 1).

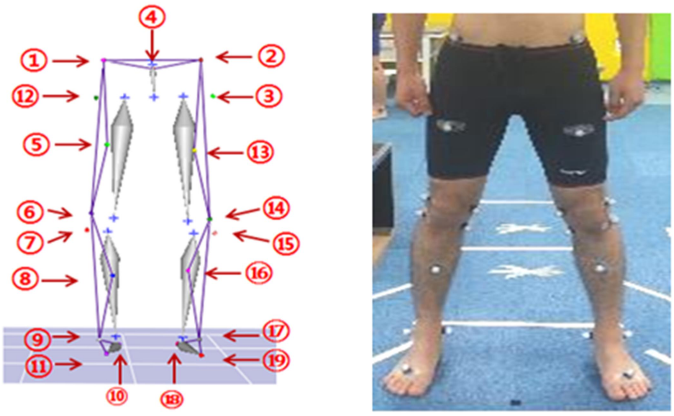

**Figure 1.** Layout of 19 reflective markers in the lower extremity

### 3. Experimental procedure

Prior to the experiment, the participants were allowed to freely warm up and stretch for 10 min. After affixing the markers, the participants practiced going on top of a box, 35 cm in height, and performing single-legged landing on the ground. After three to four practice trials, participants performed single-legged landings repeatedly (five trials per each condition) according to designated conditions of landing foot orientations, respectively. The height of the box, 35 cm, was set as the average value used in previous studies (Cho & Kim, 2011; Eun, Yang, Kim, Kang, & Kwak, 2012; Ishida et al., 2013; Lee, Kim, Cho, & Moon, 2010).

Landing foot orientations were defined as neutral (N) when the toes pointed straight forward; toe-out (TO) when the toes pointed outward at 30° relative to N; and toe-in (TI) when the toes pointed inward at 30° relative to N (Figure 2). The experimental order of landing foot orientations followed the counter-balanced design. White athletic tape was placed on the ground to ensure consistent landing foot orientation for all participants. Moreover, the participants were instructed to perform the landing motions while bare-footed to eliminate external factors associated with shoe characteristics. There were no restrictions on arm position and a 1-min rest period was given in-between landing trials to reduce fatigue from repeated measures. The participants were instructed to face forward to encourage natural landing motion.

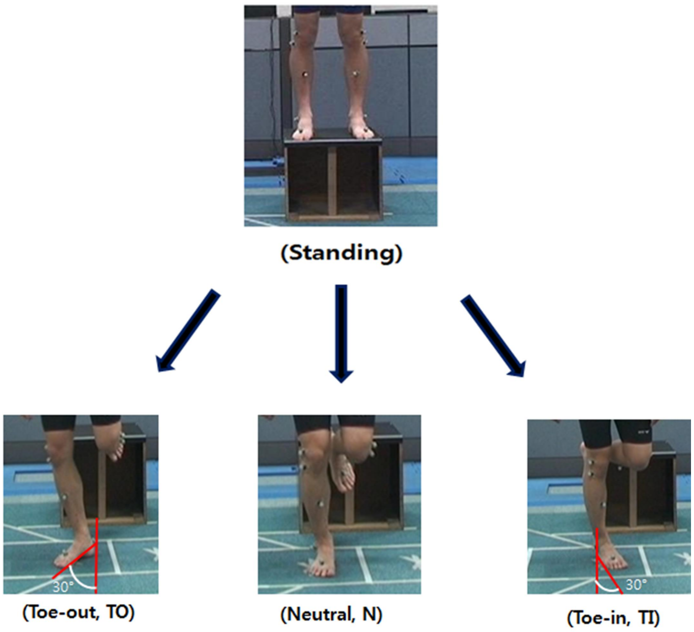

**Figure 2.** Standing position on the box and three different rotated foot placement positions

## 4. Data processing

Landing motion was divided into two major events and one phase. The first event was defined as the foot contact (FC) instant when the foot touched the ground, and the second event was defined as the maximum knee flexion (MK) instant when the knee flexed maximally at the bottom of the landing motion. The downward phase is the time period between FC and MK (Cho, Kim, Moon, Cho, & Lee, 2010).

The position data of measured reflective markers were passed through a low pass filter (Butterworth low pass 4th order filter) with cutoff frequency of 8 Hz in Cortex 4.0®, while GRF data were passed through same low pass filter with cutoff frequency of 50 Hz (Decker et al., 2003; Sinsurin, Vachalathiti, Jalayondeja, & Limroongreungrat, 2013). Using the smoothed markers' data, three-dimensional local coordinate axes for each segment were defined. Moreover, Kinetic 2.0® (Motion Analysis Cooperation, USA) module was used to calculate the three-dimensional knee joint angle, resultant joint moment, and knee joint force. The body segment parameters used in inverse dynamics analysis followed the moment of inertia, location of center of gravity (COG), and body mass values used by De Leva (1990).

The following dependent variables were used in statistical analysis. The downward phase time was the time from FC to MK, representing COG deceleration. The knee joint angle, the Cardan angles, was computed by the relationship of direction cosines formed in the local coordinate systems of the shin segment relative to the thigh segment. This is the angle that describes the movement of the distal (shin) relative to the proximal (thigh) segment. In accordance with conventional rules, the first rotation was defined as flexion/extension, the second rotation as valgus/varus, and the third rotation as internal/external rotation (Siegler et al., 2002). GRF was defined as the antero-posterior (AP), medio-lateral (ML), and supero-inferior (SI) directions relative to the participant. And knee joint moment was defined as the flexion/extension (sagittal plane), valgus/varus (coronal plane), and internal/external rotation (transverse plane) moments, respectively. GRF and joint moment were normalized by the body weight and height of each participant. The instant of FC was numerically defined when GRF exceeded 8 N (Cho et al., 2010). The maximum values generated in each direction immediately after FC (during the first 50 ms) were selected to represent the maximum GRF and joint moment, which were used in the statistical analysis (Shin et al., 2009).

## 5. Statistical analysis

One-way repeated measure ANOVA was performed on each variable for null hypothesis testing. The three different landing foot orientations were the factors, while the significance level was set to 0.05. When the main effect was observed, Bonferroni's multiple comparison test was used to identify its cause.

# RESULTS

## 1. The downward phase time

The results of downward phase time (from FC to MK) are shown in Table 1, which showed statistically significant differences according to landing foot orientation ($F(2, 32) = 4.10$, $p < .05$). In the Bonferroni's multiple comparison test, N and TO showed significantly longer downward phase time than TI ($p < .05$).

## 2. Knee joint angle

Changes in knee joint angle during landing are shown in Table 2. All three-dimensional joint angles showed significant differences according to landing foot orientation. Flexion angle was influenced by the main effect at both FC ($F(2, 32) = 13.01$, $p < .05$) and MK ($F(2, 32) = 8.24$, $p < .05$). At FC, N and TI showed significantly larger flexion angle than TO, whereas at MK, N showed significantly larger flexion angle than TI and TO. In valgus/varus angles, the effects of foot orientation changes were found at both FC ($F(2, 32) = 21.40$, $p < .05$) and MK ($F(2, 32) =$

**Table 1.** The downward phase times according to different landing foot orientations (unit: sec)

| | TI | N | TO | $F$ | $p$ | |
|---|---|---|---|---|---|---|
| FC-MK | 0.16±0.06 | 0.18±0.06 | 0.18±0.07 | $4.10^{*}$ | 0.03 | N, TO >TI |

$^{*}p < .05$ TI: toe-in, N: neutral, TO: toe-out, FC: foot contact, MK: maximum knee flexion

60.51, $p$ <.05). At FC, N showed the largest valgus angle, followed consecutively by TI and TO. At MK, TO showed the largest varus angle, followed consecutively by N and TI. Internal and external rotations on the transverse plane were significantly influenced by the main effect at both FC ($F$(2, 32) = 97.45, $p$ <.05) and MK ($F$(2, 32) = 8.237, $p$ <.05). At FC, TI showed the largest internal rotation angle, followed consecutively by N and TI. At MK, TO showed the largest external rotation angle, followed consecutively by N and TI.

**Table 2.** Changes in knee joint angle according to different landing foot orientations (unit: °)

| | | FC | MK |
|---|---|---|---|
| Flexion | TI | 21.30±4.68 | 37.33±5.76 |
| | N | 20.99±3.91 | 40.87±7.59 |
| | TO | 18.76±3.69 | 39.75±7.63 |
| | $F$ | 13.01$^{***}$ | 8.24$^{***}$ |
| | $p$ | .001 | .001 |
| | | (N, TI > TO) | (N > TI, TO) |
| Valgus (-)/ Varus (+) | TI | -1.77±4.48 | 21.46±5.90 |
| | N | -4.40±5.36 | 28.92±7.04 |
| | TO | -7.29±6.70 | 36.17±9.50 |
| | $F$ | 21.40$^{***}$ | 60.51$^{***}$ |
| | $p$ | .001 | .001 |
| | | (N > TI > TO) | (TO > N > TI) |
| Internal (-)/ External (+) Rotation | TI | -6.16±17.10 | 21.46±5.90 |
| | N | -16.96±13.77 | 28.92±7.04 |
| | TO | -33.08±12.08 | 36.17±9.50 |
| | $F$ | 97.45$^{***}$ | 8.237$^{***}$ |
| | $p$ | .001 | .001 |
| | | (TI > N > TO) | (TO > N > TI) |

$^{***}p$ <.001 TI: toe-in, N: neutral, TO: toe-out, FC: foot contact, MK: maximum knee flexion

## 3. Maximum ground reaction force

The results of maximum GRF generated after FC are shown in Table 3. The three-dimensional directions showed significantly differences according to landing foot orientation. The maximum GRF value in AP direction was the biggest in N (the backward direction), followed consecutively by TI and TO ($F$(2, 32) = 178.807, $p$ <.001). With respect to the maximum GRF value (the medial direction) in ML direction, TI showed bigger value than N and TI ($F$(2, 32) = 3.560, $p$ <.001). With respect to the maximum GRF value in SI direction, TI and N showed bigger value than (the upward direction) TO ($F$(2, 32) = 2.688, $p$ <.001).

**Table 3.** Maximum ground reaction force in three directions (Unit: N/BW)

| | AP | ML | SI |
|---|---|---|---|
| TI | -.10±.04 | .38±.10 | 1.35±.22 |
| N | -.25±.06 | .28±.09 | 1.41±.23 |
| TO | .08±.07 | .33±.11 | 1.25±.30 |
| F | 178.807 | 20.704 | 2.688 |
| P | .001$^{***}$ | .001$^{***}$ | .001$^{***}$ |
| | (N > TI > TO) | (TI > N, TO) | (TI, N > TO) |

$^{***}p$ <.001 TI: toe-in, N: neutral, TO: toe-out, AP: antero(+)-posterior(-) direction, ML: medio(+)-lateral(-) direction, SI: superior(+)-inferior(-) direction

## 4. Knee joint force

Changes in knee joint force after FC are shown in Table 4. The results showed no significant differences in all three-dimensional directions.

**Table 4.** Knee joint force (Unit: N/BW)

| | AP | ML | SI |
|---|---|---|---|
| TI | 2.63±1.81 | -.56±.76 | .41±.60 |
| N | 2.41±1.35 | -.60±.92 | .23±.67 |
| TO | 2.60±1.66 | -.40±.97 | .35±.98 |
| F | .176 | .807 | .499 |
| P | .840 | .382 | .612 |

TI: toe-in, N: neutral, TO: toe-out, AP: antero(+)-posterior(-) direction, ML: medio(+)-lateral(-) direction, SI: superior(+)-inferior(-) direction

## 5. Knee joint moment

Changes in knee joint moment after FC are shown in Table 5. The results showed no significant differences in all three anatomical planes.

**Table 5.** Knee joint moment (Unit: Nm/BW*H)

| | Sagittal | Coronal | Transverse |
|---|---|---|---|
| TI | .09±.12 | .41±.29 | .004±.01 |
| N | .08±.10 | .35±.22 | .008±.01 |
| TO | .06±.15 | .38±.29 | .007±.01 |
| F | .498 | .322 | .790 |
| P | .612 | .727 | .462 |

TI: toe-in, N: neutral, TO: toe-out

## DISCUSSION

The present study aimed to investigate the load exerted on the knees according to landing foot orientations during a single-legged landing to determine foot orientations vulnerable to knee injury. Based on this objective, the participants were instructed to intentionally land in TI (30° inward rotation of the foot) and TO (30° outward rotation of the foot) orientations and compared the results to when landing was executed in N orientation (neutral position of the foot) under the same conditions. The results showed that the different landing foot orientations at FC caused the main effects on three-dimensional joint angles and the GRFs in all AP, ML, and SI directions, respectively.

With proper landing postures, the shock absorption by knee flexion occurs immediately after ground contact mainly in the sagittal plane (Dufek et al., 1990). If the knees point inward or outward after ground contact, varus or valgus moment is generated on the coronal plane, which results in combined loading (Boden et al., 2000). In addition, from a functional anatomical perspective, the locked-knee (the locking by femur and tibia) is opened in accordance with increasing knee flexion, allowing degrees of freedom of internal/external tibial rotations. This might causes internal/external rotation moment and/or valgus/varus moment to increase combined loadings on knee (Shin et al., 2009; Joo et al., 2014). Since the knee primarily functions as a hinge joint between tibia and femur, the allowance of non-sagittal movements such as valgus/varus and internal/external rotations could lower knee stability and increase the risk of non-contact cruciate ligament injury as well.

With respect to the kinematics results in the present study, N and TI showed higher values than TO in the knee flexion angle at FC. Non-contact knee injuries are known to occur in case of small knee flexion angle (<30°) at the moment of ground contact and within 50 ms after FC (Boden et al., 2000; Shimokochi et al., 2008; Olsen et al., 2004). Smaller knee flexion angle lessens the function of the hamstrings that prevents the forward displacement of the tibia relative to the femur, whereby the cruciate ligament must withstand most of the load. Here, if joint moment in non-sagittal planes is simultaneously loaded (i. e., combined loading), the knees become even more vulnerable to sports injuries. Having a significantly small knee flexion angle at landing, as with TO orientation, represents a very poor posture with respect to injury mechanism.

In the downward phase, the range of motion of knee flexion was the biggest in N orientation (19.9°) and smallest in TI orientation (16.0°). In particular, TI orientation had significantly shorter downward phase time than other orientations. This can be interpreted as TI orientation having knee locking at the moment of FC, which made further flexion of the knee difficult (Ishida et al., 2013; Shimokochi et al., 2008). At the instant of impact, having short contact time and narrow range of joint motion might cause increased impact force on joint. Accordingly, although not statistically significant, the maximum values of joint force and joint moment were higher in TI orientation than in other orientations. In other words, combined loading on the coronal plane may highly likely occur with TI orientation.

Regarding joint angles on the coronal plane, the knee angle changed from varus to valgus immediately after FC regardless of landing foot orientations. This movement represents the adaptation of the body to secure knee stability with preventing the body from collapsing inward when landing. A study by Cho et al. (2010) demonstrated similar results indicating valgus angle appeared to prevent the body from moving in different directions in case of single-legged landing with the upper body pointing in different directions (i.e., outward, inward, and front directions, respectively). Thus, the results of current study were considered in accordance with those of Cho et al. (2010).

About the maximum GRF with 50 ms immediately after FC, TO orientation showed the lowest maximum GRF in SI direction, whereas the largest GRF in anterior direction occurred in comparison with posterior GRF in other conditions. From an injury mechanism perspective, absorbing shock in SI direction is the most preferable for the knees, whereas GRF in ML or AP direction has negative effects on knee. Therefore, decreased dependence on GRF in SI direction in TO orientation can be viewed as unwanted results. Unlike in TI and N orientations, anterior GRF occurred in TO orientation. This can increase the resistive load of the anterior cruciate ligament due to inducing inertial force that cause anterior displacement of the tibia. In addition, external rotation angle of the tibia in downward phase appeared much higher with TO orientation than other orientations, indicating the possibility of higher knee instability (Boden et al., 2000; Noyes et al., 1983; Olsen et al., 2004; Shimokochi et al., 2008).

No statistically significant differences were observed in the inverse dynamics results, represented by maximum joint force and moment of the knees, which may be associated with the limitations of the present study. First, since the participants were already cognizant of their landing postures, they would not have allowed their body to be exposed to loading that would possibly cause injury. In other words, although the experiment artificially required TO and TI orientations, the participants may not have maintained TI and TO orientations with exactly 30° of inward and outward rotation, respectively, due to their flexibility and the protection mechanism of knee injury. Moreover, because the participants were forced to consciously move the feet in certain orientations, the landing may have been somewhat awkward, rather than being natural. Therefore, the findings in the present study may be used as basic data for identifying the causes of non-contact knee injuries, but these may be far from accurately reflecting the actual injury situations.

In summary, the findings in the study showed that a neutral (N) landing foot orientation should be preferable to minimize combined loading exerted on the knees. N orientation can be viewed as the posture that maximizes GRF in SI direction and minimizes GRF in ML direction, to reduce the moment on the coronal plane and facilitate shock absorption by knee flexion. The landing posture of N orientation can be achieved through training in terms of strengthening of muscles surrounding the knees and maintaining flexibility in the knees. In addition, the semimembranosus and semitendinosus muscles in the hamstrings must form a balance with biceps femoris muscle, while maintaining balance between the vastus medialis and lateralis in the quadriceps.

## CONCLUSION

The present study conducted biomechanical analysis on the changes in knee movement and load exerted on the knees according to landing foot orientation during a single-legged landing to determine foot orientation vulnerable to knee injury. Conclusively, TI and TO orientations should be avoided with respect to the risk of knee injury. TI orientation has short downward phase time and can cause combined loading on the control plane from large ML GRF. Meanwhile, TO orientation can cause undesirable anterior GRF to stress the anterior cruciate ligament and induce excessive external rotation in the tibia. Therefore, landing in N orientation is the most preferable foot orientation to reduce the risk of knee injury with minimizing combined loading.

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