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Research article

The Effect of Landing Surface on the Plantar Kinetics of Chinese Paratroopers Using Half-Squat Landing

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Abstract

The objective of the study was to determine the effect of landing surface on plantar kinetics during a half-squat landing. Twenty male elite paratroopers with formal parachute landing training and over 2 years of parachute jumping experience were recruited. The subjects wore parachuting boots in which pressure sensing insoles were placed. Each subject was instructed to jump off a platform with a height of 60 cm, and land on either a hard or soft surface in a half-squat posture. Outcome measures were maximal plantar pressure, time to maximal plantar pressure (T-MPP), and pressure-time integral (PTI) upon landing on 10 plantar regions. Compared to a soft surface, hard surface produced higher maximal plantar pressure in the 1st to 4th metatarsal and mid-foot regions, but lower maximal plantar pressure in the 5th metatarsal region. Shorter T-MPP was found during hard surface landing in the 1st and 2nd metatarsal and medial rear foot. Landing on a hard surface landing resulted in a lower PTI than a soft surface in the 1stphalangeal region. For Chinese paratroopers, specific foot prosthesis should be designed to protect the1st to 4thmetatarsal region for hard surface landing, and the 1stphalangeal and 5thmetatarsal region for soft surface landing.

Key words: Half-squat landing, plantar kinetics, plantar pressure, surface reaction force, pressure time integral.

Introduction

Parachute landing is a demanding maneuver for paratroopers. Chinese paratroopers use half-squat landing skills, which is different from the parachute landing technique used in Western countries (Bricknell et al.,1999). Half-squat landing is characterized by simultaneous contact of two feet on the surface to diminish the energy of falling. Parachute landing accounts for the leading cause of injuries for Chinese paratroopers, with the injuries mostly seen in the foot and ankle joint (Xie et al.,2004). The reported incidence of landing injuries is 69.1%, and of the landing injuries ankle sprain accounts for 25.9%, followed by calf injuries (23.5 %) and knee injuries (18.5 %) (Zhang,2005). Another cross-sectional study by Wu et al. (2010) of 6844 paratrooper recruits found that the prevalence of landing injury was 86.2%. New recruits who are not familiar with the landing skills are more likely to get injured compared to experienced senior peers. Decreasing landing injuries during paratrooper training is essential for Chinese paratroopers.

Landing on hard surface has been recognized as a risk factor for landing injuries (Hong et al.,2012;Tessutti et al.,2010). The increase in stiffness of the landing surface increases the surface reaction force and plantar pressure acting on the foot. To decrease the injury rate of paratrooper trainees, sand is currently used for ground landing training. However, paratroopers still need to land on hard surfaces such as concrete or rocky ground during training. In situations where the landing surface may do harm to the paratroopers or to the recruits who have not mastered the skills, protective footwear has been suggested as an efficient way to prevent injuries (Knapik et al.,2008;Knapik et al.,2010). However, due to different landing maneuvers, protective footwear for Chinese paratroopers has not been developed.

Understanding plantar kinetics during a half-squat landing is essential for designing protective footwear for Chinese paratroopers. However, studies on the plantar kinetics during half-squat landing are limited. Niu et al. (2011)reported the correlation of lower limb muscle activation and surface reaction force acting on the foot sole during a two-legged landing; however, the subjects were not professional paratroopers and the landing maneuvers did not follow paratrooper landing guidelines. The effect of landing surface on the biomechanical responses of different plantar regions has not been well investigated. As a result, the aim of this study is to compare the plantar kinetics between a hard surface landing and soft surface landing in a half-squat posture. The results of this study are expected to provide a reference for strategies of injury prevention. Soft surface in surface-landing training course is considered to be safer than the harsh surface encountered in other field training of parachute landing. Therefore, plantar kinetics during soft-surface landing can be seen as the reference model for making strategies to prevent injuries.

Methods

To minimize the bias of gender (Carcia et al.,2012; Shimokochi et al.,2009), the recruited participants were all male. A total of 20 elite male paratroopers with formal parachute landing training and over 2 years of parachute jumping experience were recruited and enrolled in the study. The mean age of the paratroopers was 22.6 ± 5 years, with an average body height of 1.76 ± 0.04 m, and an average body weight of 74.4 ± 8.6 kg. Subjects were eligible for participation if they were healthy and had no history of ankle, knee, and hip joint trauma or spinal fractures. Prior to participation, each subject was informed of

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the aims and protocols of this study and provided written informed consent. The study was approved by the Institutional Review Board of the Air Force General Hospital.

Intervention

Before jumping, each subject jogged for 20 minutes at a comfortable speed as a warm-up. Each subject was instructed to jump off a platform with a height of 60 cm, and land on either a hard surface or a soft surface in a half-squat posture. The size of surface was 100cm × 100cm × 30cm in depth. The hard surface was an iron plate, and the soft surface was sand. Before each jump/landing, the sand was flattened and smoothed.

Each subject performed the half-squat landing based on the standard protocol of Chinese martial paratroopers(Yu,1974). Upon hearing the order to jump, the subject jumped forward and landed on both feet with the bilateral knees, heals, and foot thumbs contacting the surface together. The bilateral hips, knees, and ankles were kept flexed until the trunk regained balance and resumed a neutral stance position. Each subject performed the half-squat landing on a hard surface or a soft surface three times, respectively.

Outcome measures

A Pedar-X® in-shoe pressure measurement system (Novel, Munich, Germany) was used to measure the plantar kinetics of each subject at a sample rate at 100 Hz. The Pedar-X insole pressure measurement system has been widely used to evaluate plantar kinetics in various of sport maneuvers, such as walking, running, cutting, jumping, and throwing (Hong et al.,2012; Orendurff et al.,2008; Tessutti et al.,2012). The repeatability and reliability of the system has been validated (Ramanathan et al.,2010). Pedar insole pressure sensors were taped to the insole of the paratrooper boots. Prior to testing, each insole pressure sensor was calibrated following the manufacturer instructions.

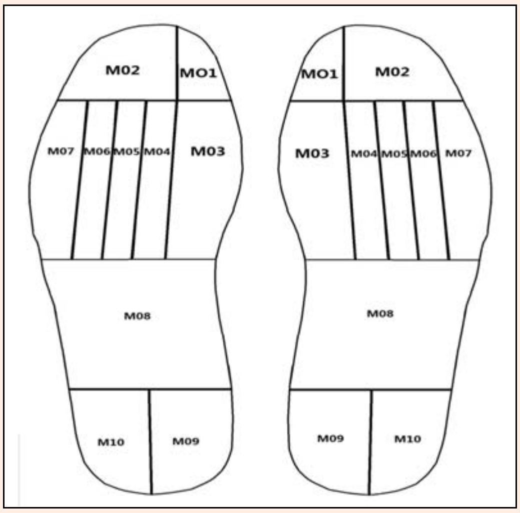

Figure 1. Schematic of the 10 anatomic regions of the foot measured by the pressure-sensitive insole. M1 = 1st phalanges, M2 = 2nd to 5th phalanges, M3 = 1st metatarsal, M4 = 2nd metatarsal, M5 = 3rd metatarsal, M6 = 4th metatarsal, M7 = 5th metatarsal, M8 = midfoot, M9 = medial heel, M10 = lateral heel.

The insole pressure sensor was divided into 10 regions corresponding to foot anatomic locations. These locations were the 1stphalanges (M1), 2nd to 5th phalanges (M2), 1st metatarsal (M3), 2nd metatarsal (M4), 3rd metatarsal (M5), 4th metatarsal (M6), 5th metatarsal (M7), midsole (M8), medial heal (M9), and lateral heal (M10) (Figure 1). These 10 regions can be further classified as forefoot section (M1-M7), mid foot section (M8), and rear foot section (M9-M10). When the subject performed the half-squat landing, the maximal plantar pressure in the vertical axis direction, time to maximal plantar pressure (T-MPP), and pressure-time integral (PTI) of each of the 10 selected regions was calculated using Pliance software (Novel, Munich, Germany).The integration of pressure over T-MPP was defined as PTI.

Data analysis

The data of three trials was averaged before statistical analysis. Repeated measures were used because this study used the same group of subjects to perform two tasks. The effect of landing surface (two level: hard and soft) and foot laterality (two level: left and right) on the three measures on each of the 10 plantar regions were investigated. Paired-t test was chosen to eliminate the effect of subject variation. A significant difference was considered at $p < 0.05$.

Results

Landing surface significantly affected maximal plantar pressure in the plantar regions M4 ($p = 0.021$), M5 ($p = 0.002$), M6 ($p = 0.011$), M7 ($p < 0.001$), and M8 ($p = 0.018$). Compared to a soft surface, a hard surface produced higher maximal plantar pressure in M4-M6 and M8, but lower maximal plantar pressure in M7.Foot laterality had a significant effect on maximal plantar pressure in plantar regions M2 ($p = 0.037$) and M7-M10 (all, $p < 0.001$). The effect of interaction between the landing surface and foot laterality on maximal plantar pressure was significant in plantar regions M3 ($p=0.004$), M7 and M8 (both, $p < 0.01$), and M9 ($p = 0.011$) (Figure 2).

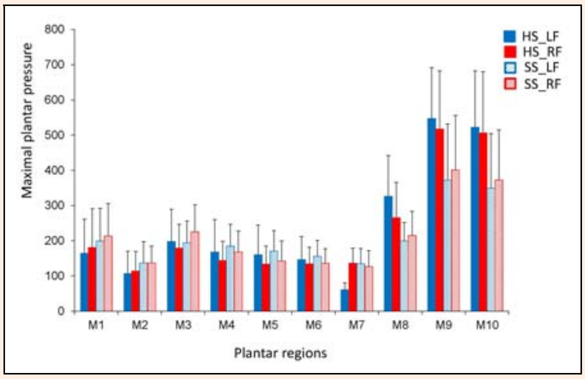

Figure 2. Maximal plantar pressure under the 10 regions of the left foot (LF) and right foot (RF) during hard surface (HG) and soft surface (SG) landings.

Landing surface significantly affected T-MPP in plantar regions M2 ($p = 0.046$), M3 ($p = 0.041$), and M9 (p = 0.033). Compared to a soft surface, a hard surface produced a shorter T-MPP in those regions. Foot laterality significantly affected T-MPP in all 10 regions (all, $p < 0.01$). The effect of the interaction between landing surface and foot laterality on T-MPP was significant in plantar regionM4 (p = 0.023) (Figure 3).

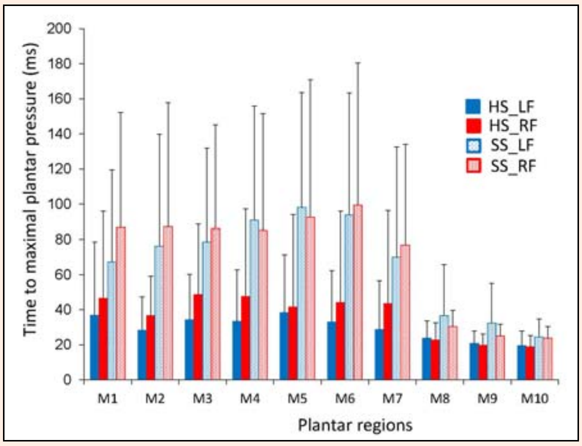

Figure 3. Surface contact time under the 10 regions of the left foot (LF) and right foot (RF) during hard surface (HG) and soft surface (SG) landings.

Landing surface significantly affected PTI in plantar region M1 (p = 0.021), in which a hard surface resulted in a lower PTI than soft surface. Foot laterality significantly affected PTI in plantar regions M1-M7 (all, $p < 0.01$). The effect of the interaction between landing surface and foot laterality on PTI was significant in plantar regions M4 (p = 0.008) and M10 (p = 0.044) (Figure 4).

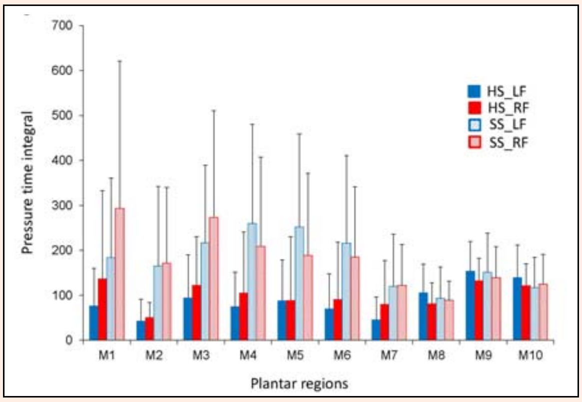

Figure 4. Pressure time integral (PTI) under the 10 regions of the left foot (LF) and right foot (RF) during hard surface (HG) and soft surface (SG) landings.

Discussion

In this study, the effect of landing surface on the full spectrum of plantar kinetics was investigated for Chinese paratroopers during a half-squat landing. To our knowledge, this study may be the first one to show the effect of landing surface on plantar biomechanics for this particular group and specific skill. The results of this study can provide a reference for protective footwear design for Chinese paratroopers.

Maximal plantar pressure has been used as an indicator of places likely to get impact injuries. An increase of the maximal plantar pressure may result in injuries below the knees, including ankle sprain and foot fractures (Arampatzis et al.,2003; Fong et al.,2008; Gittoes et al.,2013; Parsons et al.,2012; Shimokochi et al.,2009; Yeow et al.,2009). The most prominent difference of maximal plantar pressure resulting from a hard or soft landing surface was mostly observed in the metatarsal region. During a half-squat landing, the soles of the contact surface at the same time upon landing. To decelerate the jumping impact quickly, subjects tend to flex the trunk, which moves the center of mass forward and causes the vertical center of mass to pass through the metatarsal region. Forward bending of the upper trunk increases plantar flexion moments (Shimokochi et al.,2009). As a result, the material of the landing surface affects the metatarsal region more than other plantar regions. Compared to a softsurface, a hard surface resulted in higher plantar pressure from the 1st to the 4thmetatarsal. This may indicate the foot is less stable, and tends to supinate when landing on a softer surface with less rigidity.

The PTI combines the effect of plantar pressure andpressure acting duration (i.e., T-MPP in this study), and has beenconsidered an indicator of chronic injury, such as pressure ulcers in diabetic patients (Tong et al.,2011; Waldecker,2012). In this study, the difference of PTI between the hard surface landing and softsurface landing was only observed in the 1stphalangeal region, with a higher value for the soft surface landing. It is hard to determine if the difference is more from the difference of plantar pressure or the difference of pressure acting duration, because the effects of landing surface on plantar pressure and that on pressure acting duration are both insignificant. The higher PTI of the soft surface landing indicates the soft surface may subject the 1st phalangeal region to fatigue pressure, causing early degenerative changes, chronic arthritis, or fatigue fractures.

The present study also revealed the effect of foot laterality on plantar kinetics. Niu et al. (2011)reported that compared to the non-dominant side, the dominant ankle produces greater angular velocities in dorsiflexion and abduction upon a two-legged landing, and implied that the dominant ankle is at greater risk of injury. In this study, we focused on the effect of landing surface, and did not investigate the dominant foot of each subject before testing. Thus, we were not able to determine if the effect of laterality was related to foot preference.

There are some limitations to this study. First, the number of subjects was relatively small. Second, for ground landing training the standard jumping platform is 150 cm in height. In this study the height was reduce to 60 cm to reduce the risk of injury to the participants.

Conclusion

Compared to the soft surface, maximal plantar pressure is higher in the metatarsal regions, except for the

5th metatarsal, when landing on a hard surface in a half-squat posture. These metatarsal regions with higher maximal plantar pressure are at risk of impact injuries. The 1st phalangeal region is subjected to a higher PTI when landing on a soft surface. This region is at higher risk of chronic injuries. The results of the present study may assist in the design of protective footwear for Chinese paratrooper.

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Key points

- Understanding plantar kinetics during the half-squat landing used by Chinese paratroopers can assist in the design of protective footwear.
- Compared to landing on a soft surface, a hard surface produced higher maximal plantar pressure in the 1st to 4th metatarsal and mid-foot regions, but lower maximal plantar pressure in the 5th metatarsal region.
- A shorter time to maximal plantar pressure was found during a hard surface landing in the 1st and 2nd metatarsals and medial rear foot.
- Landing on a hard surface resulted in a lower pressure-time integral than landing on a soft surface in the 1st phalangeal region.
- For Chinese paratroopers, specific foot prosthesis should be designed to protect the 1st to 4th metatarsal region for a hard surface landing, and the 1st phalangeal and 5th metatarsal region for a soft surface landing.

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