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Effect of the sagittal ankle angle at initial contact on energy dissipation in the lower extremity joints during a single-leg landing

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ABSTRACT

Background: During landing, the ankle angle at initial contact (IC) exhibits relatively wide individual variation compared to the knee and hip angles. However, little is known about the effect of different IC ankle angles on energy dissipation.
Research question: The purpose of this study was to investigate the relationship between individual ankle angles at IC and energy dissipation in the lower extremity joints.
Methods: Twenty-seven adults performed single-leg landings from a 0.3-m height. Kinetics and kinematics of the lower extremity joints were measured. The relationship between ankle angles at IC and negative work, range of motion, the time to peak ground reaction force, and peak loading rate were analyzed.
Results: The ankle angle at IC was positively correlated with ankle negative work ($r = 0.80$, $R^2 = 0.64$, $p < 0.001$) and the contribution of the ankle to total (ankle, knee and hip joint) negative work ($r = 0.84$, $R^2 = 0.70$, $p < 0.001$), but the ankle angle was negatively correlated with hip negative work ($r = -0.46$, $R^2 = 0.21$, $p = 0.01$) and the contribution of the hip to total negative work ($r = -0.61$, $R^2 = 0.37$, $p < 0.001$). The knee negative work and the contribution of the knee to total negative work were not correlated with the ankle angle at IC. The ankle angle at IC was positively correlated with total negative work ($r = 0.50$, $R^2 = 0.25$, $p < 0.01$) and negatively correlated with the peak loading rate ($r = -0.76$, $R^2 = 0.57$, $p < 0.001$).
Significance: These results indicated that landing mechanics changed as the ankle angle at IC increased, such that the ankle energy dissipation increased and redistributed the energy dissipation in the ankle and hip joints. Further, these results suggest that increased ankle energy dissipation with a higher IC plantar flexion angle may be a potential landing technique for reducing the risk of injury to the anterior cruciate ligament and hip musculature.

1. Introduction

Single-leg landing is a demanding task on the ankle joint because the ankle joint and surrounding tissues initially and partially absorb and dissipate the high impact force, ranging from approximately 2.0 to 5.0 times the body weight (BW) [1–3]. The ankle joint plays an important shock absorption role through the musculotendinous units around the ankle joint [4]. Generally, the ankle plantar flexors provide 30 to 50% of the shock absorption that occurs during landing [1,2,5]. Thus, inadequate shock absorption through the ankle joint can increase energy dissipation demand on the proximal joints in the lower extremities [1,6]. This process can injure the knee joint, thereby causing meniscus damage and anterior cruciate ligament (ACL) rupture [1,2,6].

The magnitude and relative contribution to shock absorption in the lower extremity joints by muscular energy dissipation (negative work) has been suggested to be altered by adjusting the ankle angle at initial contact (IC) [5,6]. Additionally, the ankle angle at IC affects the ground reaction force (GRF) and range of motion (ROM) of the ankle and is associated with risk of injury to the lower extremities during landing [6–8]. A higher ankle plantar flexion at IC has been suggested to be associated with an increase in ankle ROM and a decrease in the peak vertical GRF (vGRF) during landing [7]. Greater ankle ROM can increase the time to peak vGRF and decrease the loading rate [6], thus reducing the impact stress on soft tissues during landing [8]. Therefore, one expects that the IC ankle angle and/or ankle kinematics largely influence shock absorption during single-leg landing.

Recent studies have reported that the ankle angle at IC is linearly or nonlinearly related to shock absorption during running [9,10]. Previous

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studies have reported the effects of forefoot and rearfoot landing on knee loading patterns and GRF during single-leg landing [11,12]. However, these studies mainly reported the discrete comparative shock absorption between a forefoot and rearfoot strike [11–14]. There is individual variation in the lower extremity joint angle on IC in the sagittal plane during landing, and the ankle angle at IC exhibits a wider individual variation than knee and hip angles[13]. Currently, little is known regarding the effect of different ankle joint angles at IC on shock absorption during single-leg landing. A detailed examination of individual ankle landing techniques at IC will provide insight into the energy dissipation capacity of the ankle and the lower extremities.

In addition, the amount of energy absorbed by the plantar flexor is known to change depending on the ankle landing technique [14]. Self and Panie [14] examined four differently instructed landing techniques at the ankle joint and found that the amount of energy absorbed by the Achilles tendon was largest when subjects were instructed to land as softly as possible by absorbing the impact through the toes and the ankle flexors. Although this result suggests that differences in ankle landing technique lead to the differences in ankle energy dissipation, no studies have yet examined the relationship between ankle angle at IC and ankle energy dissipation.

Therefore, one might expect that individual variation in the IC ankle angle changes the amount of energy dissipation in the ankle joints and the contribution of the lower extremity joints to shock absorption during single-leg landing. The purpose of this study was to examine the relationship between individual ankle angles at IC and the energy dissipation in the lower extremity joints during single-leg landing. In this study, the following hypotheses were tested: (1) the ankle angle at IC is positively correlated with the amount of energy dissipation in the ankle joint during single-leg landing; and (2) plantar flexion in the ankle angle at IC alters the relative contribution of the ankle, knee and hip joint to total energy dissipation during single-leg landing.

2. Methods

Twenty-seven healthy participants (age: 21.4 ± 1.8 years, height: 1.71 ± 0.08 m, mass: 66.8 ± 12.1 kg, 19 males, 10 females) without any current symptoms of pain or a history of lower extremity musculoskeletal injuries requiring surgery were recruited. All the participants wore the same running shoes (Nike Air Pegasus 30; Nike, Beaverton, OR, USA) and signed an informed consent approved by the University's Institutional Review Board.

A floor-embedded force plate (9260AA6; Kistler, Winterthur, Switzerland) was used to measure the GRF data at 1200 Hz. A motion-capture system (Eagle; Motion Analysis Corp., Santa Rosa, CA, USA) with 8 cameras was employed to collect kinematic data at a sampling rate of 400 Hz. The force plate was synchronized with the motion-capture system. Reflective markers (Φ12.5-mm spheres) were attached to anatomical bony landmarks as indicated in Fig. 1a [15].

The participants were instructed to perform a single-leg drop landing by stepping off of a 0.3-m platform [16] with the dominant foot onto the force plate (Fig. 1b). The dominant leg was defined as the more comfortable leg for single-leg landing and/or kicking a ball. The subjects folded their arms across their chest and stepped off the platform without jumping up. They were instructed to remain balanced on their dominant leg for at least 2 s after landing. The participants were asked to use their natural landing style except for a rearfoot strike and practiced landing until they appeared comfortable with the landing task, and a 5-min rest was provided prior to the actual trial. A trial was considered successful when a participant stepped off the platform and adopted a stable landing posture without losing his/her balance. Two trials were performed per landing task, and the results were averaged.

The measured kinematic and kinetic data were filtered using a zero-lag fourth-order Butterworth low-pass filter at a cutoff frequency of 10 and 40 Hz, respectively. The joint angle and angular velocities were calculated from the filtered 3D marker coordinate data [15]. The joint angle at IC, joint ROM, joint angular velocity, peak vGRF, time to peak vGRF, peak loading rate, joint moment, joint power and joint energy dissipation for the ankle, knee and hip joints of the dominant leg during the landing phase were obtained. The landing phase was the time between IC (over 20 N [15]) and the peak ankle dorsiflexion angle.

Joint ROM was calculated from the difference between the joint angle at IC and the joint angle at maximum knee flexion. Internal joint moment values were calculated using inverse dynamics. Joint power was calculated as the product of joint moment and joint angular velocity. Mechanical joint work was defined as the integral of joint power over time, whereby negative work represented energy dissipation by the joint muscles. Joint work was normalized to BW. Individual contributions of the hip, knee, and ankle to energy dissipation were calculated as a percentage of their respective values to the total the negative work because the negative work values indicate energy dissipation through eccentric muscular contraction [17]. The peak vGRF was normalized to BW, and the peak loading rate was calculated as the peak vGRF divided by time to peak vGRF.

Pearson correlation analyses were performed to test the relationships between the ankle angle at IC and ankle negative work, knee negative work, hip negative work, total negative work, peak ankle angular velocity, peak knee angular velocity, peak hip angular velocity, ankle ROM, knee ROM and hip ROM in the sagittal plane. In addition, a linear regression analysis was performed to test the relationship between the ankle angle at IC and the peak vGRF, time to peak vGRF and peak loading rate. All statistical analyses were performed at a significance level of 0.05 using MATLAB R2014a (MathWorks, Natick, MA, USA).

3. Results

The mean value (± standard deviation) of the IC ankle angle during a single-leg landing was −11.5 ± 13.1°, and the IC ankle angle in twenty-seven individuals ranged from −27.8° to 27.8°. The mean vGRF data indicated that one peak profile was commonly observed during single-leg landing (Fig. 2a). The peak ankle angular velocity occurred before the peak vGRF, and the peak knee and hip angular velocity occurred after the peak vGRF (Fig. 2a). In addition, the peak ankle negative power occurred before the peak vGRF, and the peak knee and hip negative power occurred after the peak vGRF (Fig. 2a). The mean value (± standard deviation) of total negative work was 2.66 ± 0.42 J/kg (Fig. 2b). The largest absolute and relative negative work values were calculated for the knee, followed by the ankle and hip (Fig. 2b, c).

The ankle angle at IC was positively correlated with ankle negative work (r = 0.80, $p < 0.001$, Fig. 3a) and total negative work (r = 0.50, $p < 0.01$). The ankle angle at IC showed a significant negative correlation with hip negative work (r = −0.46, $p < 0.05$, Fig. 3a), but no significant correlation was observed between the ankle angle at IC and knee negative work (r = 0.08, $p = 0.68$, Fig. 3a).

In addition, the ankle angle at IC was positively correlated with the relative contribution of the ankle joint to total negative work (r = 0.84, $p < 0.001$, Fig. 3b) but was negatively correlated with the relative contribution of the hip joint to total negative work (r = −0.61, $p < 0.001$, Fig. 3b). There was no significant correlation between the ankle angle at IC and the contribution of the knee joint to total negative work (r = −0.36, $p = 0.11$, Fig. 3b).

The ankle angle at IC showed a positive correlation with ankle ROM (r = 0.93, $p < 0.001$, Table 1), knee ROM (r = 0.44, $p < 0.05$, Table 1) and hip ROM (r = 0.45, $p < 0.05$, Table 1). Significant positive correlations were also observed between the ankle angle at IC and the peak ankle (r = 0.93, $p < 0.05$, Table 1) and the knee angular velocity (r = 0.45, $p < 0.05$, Table 1). However, there was no significant correlation between the ankle angle at IC and the peak hip angular velocity (r = 0.26, $p = 0.18$, Table 1).

In addition, the ankle angle at IC showed a significant negative correlation with the peak loading rate (r = −0.75, $p < 0.001$, Table 1)