Prophylactic Ankle Braces and the Kinematics and Kinetics of Half-Squat Parachute Landing

Di Wu; Chao Zheng; Ji Wu; Tan Hu; Rongrong Huang; Lizhen Wang; Yubo Fan

INTRODUCTION: The objective of the study was to investigate the effects of dropping heights and prophylactic ankle braces on ankle joint biomechanics during half-squat parachute landing from two different heights.

METHODS: There were 30 male elite paratroopers with formal parachute landing training and more than 2 yr of parachute jumping experience who were recruited for this study. The subjects tested three different ankle brace conditions (no-brace, elastic brace, semirigid brace). Each subject was instructed to jump off a platform from two different heights of 0.4 m and 0.8 m, and land on a force plate in a half-squat posture. The Vicon 3D motion capture system and force plate were used to record and calculate kinematic and kinetic data.

RESULTS: Dropping height had a significant effect on peak vertical ground reaction force (vGRF), maximum ankle angular displacement, and time to vGRF. As compared with the no-brace group, use of an elastic ankle brace significantly reduced peak vGRF by 18.57% and both braces significantly reduced the maximal angular displacements of dorsiflexion. The semirigid brace provided greater restriction against maximal angular displacement of inversion.

DISCUSSION: The elastic and semirigid ankle braces both effectively restricted motion stability of the ankle joint in the sagittal plane, and the semirigid ankle brace prevented excessive inversion, although the comfort of this device should be improved overall.

KEYWORDS: Half-squat landing, dropping height, prophylactic ankle brace, kinematics, kinetics.

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Landing injury is the most frequent of all parachuting injuries and ankle joint injury is the most common landing injury. Ekeland[2] pointed out that ankle injury accounted for 27.3% and 21.9% among free fall and fixed rope parachute landing injuries, respectively. A Norwegian survey showed that the lower extremities were the most common site of parachuting injuries, with ankle injuries accounting for 36% of all cases. This incidence was 32.8% in a study in Brazil. A similar report from the United States reported an incidence of ankle injury of 63.6%. In China, an epidemiological study by Li et al. found that 454 out of 1675 parachutists suffered ankle injury at least once during parachute jumping, and 922 out of 4081 during training.[2,4,6]

The causes and mechanisms of ankle injury during parachute landing are multifaceted and complex. Analysis of 4499 parachute landing injuries showed that about 71% of such injuries were caused by an incorrect landing posture, resulting in potentially injurious ankle kinematics and high vertical ground reaction force (vGRF), which further aggravates ankle sprain.[2] A previous study classified the causes of parachute landing injury into three mechanisms—inversion, eversion, and compression—with the first two accounting for 59.3% and 30.7% of injuries, respectively. Therefore, inversion appears to be the main mechanism of parachute landing ankle injury. However, most studies of parachute landing injury of the ankle joint mainly focused on epidemiological investigations, cadaver modeling systems, and primitive kinematic/kinetic studies. The experimental equipment (high-speed camera and general force plate) used in these studies are now outdated and the subjects

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were not active paratroopers. Due to the high rate of injury with parachute landing, there is a need to better understand the 3D mechanics that occur during this common military exercise.

In the early 1990s, Aircast, Inc. (Vista, CA), developed an outside-the-boot parachute ankle brace (PAB), which is composed of a hard plastic shell and closed air bags to protect the medial and lateral malleoli. The PAB was designed to prevent excessive inversion and eversion, while allowing dorsiflexion and plantar flexion. The PAB was found to reduce the incidence of ankle injury by about 50% and is a cost-effective device that should be worn during military operations to reduce the risk of ankle injury.[3] In recent years, the ankle brace has been undergoing rapid development and has been widely applied in various sports, medical treatments, and military maneuvers. However, no prophylactic PAB has yet been developed for the different landing maneuvers of parachutists. An experimental biomechanical study of half-squat landing is essential to design an effective prophylactic PAB. The aim of this study is to compare the kinematic and kinetic data of the ankle joint during simulated half-squat parachute landing from two different dropping heights under three different ankle brace conditions (no-brace, elastic ankle brace, and semirigid ankle brace). The results of this study are expected to provide a reference for the design and improvement of a prophylactic PAB.

METHODS

Subjects

There were 30 elite male paratroopers (mean age, 22.40 ± 3.38 yr; mean height, 179.46 ± 5.17 cm; mean weight, 70.97 ± 7.85 kg) with formal parachute landing training and more than 2 yr of parachute jumping experience who volunteered to participate in this study. All subjects had right dominant legs, which was determined by asking each individual which leg they would use to kick a ball as far as possible. All eligible subjects were healthy with no history of lower extremity trauma or spinal fractures. None of the subjects had a history of previous surgery of the lower extremities, neurological or joint degenerative disease, or vestibular or visual disturbance. Each subject was informed of the aims and protocols of this experiment and submitted informed consent before participation. The study protocol was approved by the Institutional Review Board of the Air Force General Hospital of Chinese People's Liberation Army, Beijing, China. All experiments were performed in the Key Laboratory for Biomechanics and Mechanobiology of the Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, Beijing, China.

Equipment

A force plate (SMA-6, AMTI, Watertown, MA) was used to measure vGRF. The force plate and surrounding floor had similar surface properties to avoid any potential imbalance. A three-dimensional (3D) motion capture system (Vicon, Oxford Metrics, Oxford, UK) was used to obtain kinematic data. The reflective surface marker sets were tightly attached to the corresponding bony landmarks (including the forehead, occipitalia, shoulder, upper arm, elbow, wrist, the second and fifth heads of the metacarpal bone, the anterior superior and posterior superior iliac spines, the greater trochanter, thigh, knee, shank, ankle, heel, the first, second, and fifth heads of the metatarsal bone, the seventh cervical and tenth thoracic vertebra, the clavicular head, and the manubrium sterni). Eight cameras (CMOS, Vicon, Oxford Metrics, UK) containing sensors recorded the entire simulated parachute jump in a half-squat posture.

Two commercially available types of ankle braces were used in this experiment: an elastic ankle brace (AQ5261EA, Atlas Co., Ltd, Beijing, China) and a semirigid ankle brace (LP787, LP Co., Ltd, Seattle, WA). The body of the elastic ankle brace was composed of an ultra-thin material, in which the inner shell was constructed of a high-elastic antiskid mesh fabric and the outer shell was constructed of a high-elastic shock-absorbing foam. Two straps crossing from the planta in a figure eight pattern were pressurized and fixed at the lateral and medial malleoli to strengthen the stability of the ankle joint. The semirigid ankle brace contained a U-shaped semirigid metal spring that functioned as a "hoop" at the lateral and medial malleoli.

Procedure and Data Collection

Before jumping, each subject jogged for 5 min at a comfortable speed as a warm-up, then performed the half-squat parachute landing. Upon hearing the order to jump, the subject jumped forward and flexed lower limbs with knees, ankles, and forefeet hugging each other and with the plantar parallel to the ground, which was called "three hugging and one parallel" in the teaching material of the China Airborne School, then landed on the force plate until the trunk stopped moving and resumed a neutral stance.[6] The subjects were evaluated under three different ankle brace conditions (no-brace, elastic ankle brace, and semirigid ankle brace) and instructed to start and terminate the drop landing movement in a standing position, to jump off and touch down with both feet, to lean forward with the body while jumping, and finally to stop the fall in a half-squat position smoothly (**Fig. 1A**). Each subject performed this maneuver from two different heights (low: 0.4 m and high: 0.8 m), undergoing five trials under each condition. The order of the experimental condition was random to prevent any order effects. Any fatigue effects were mitigated by resting for at least a 60-s interval between landings under each condition. The subjects wore short pants that exposed the skin of the lower extremities to allow convenient attachment of the reflective surface markers and enhance observation of body alignment during the tests.

Each subject landed on the force plate, which collected GRF signals at a sample frequency of 1500 Hz. In five successful trials under each condition, GRF data were measured in the dominant foot. All vGRF values were normalized to bodyweight (BW). The time to peak vGRF, which started from the initial contact with the force plate, was another important variable to evaluate the influence of each factor. The surface reflective markers were tightly attached to each corresponding bony landmark with Velcro. A 3D motion capture system was used to measure the 3D position of reflective markers in a global reference frame at a

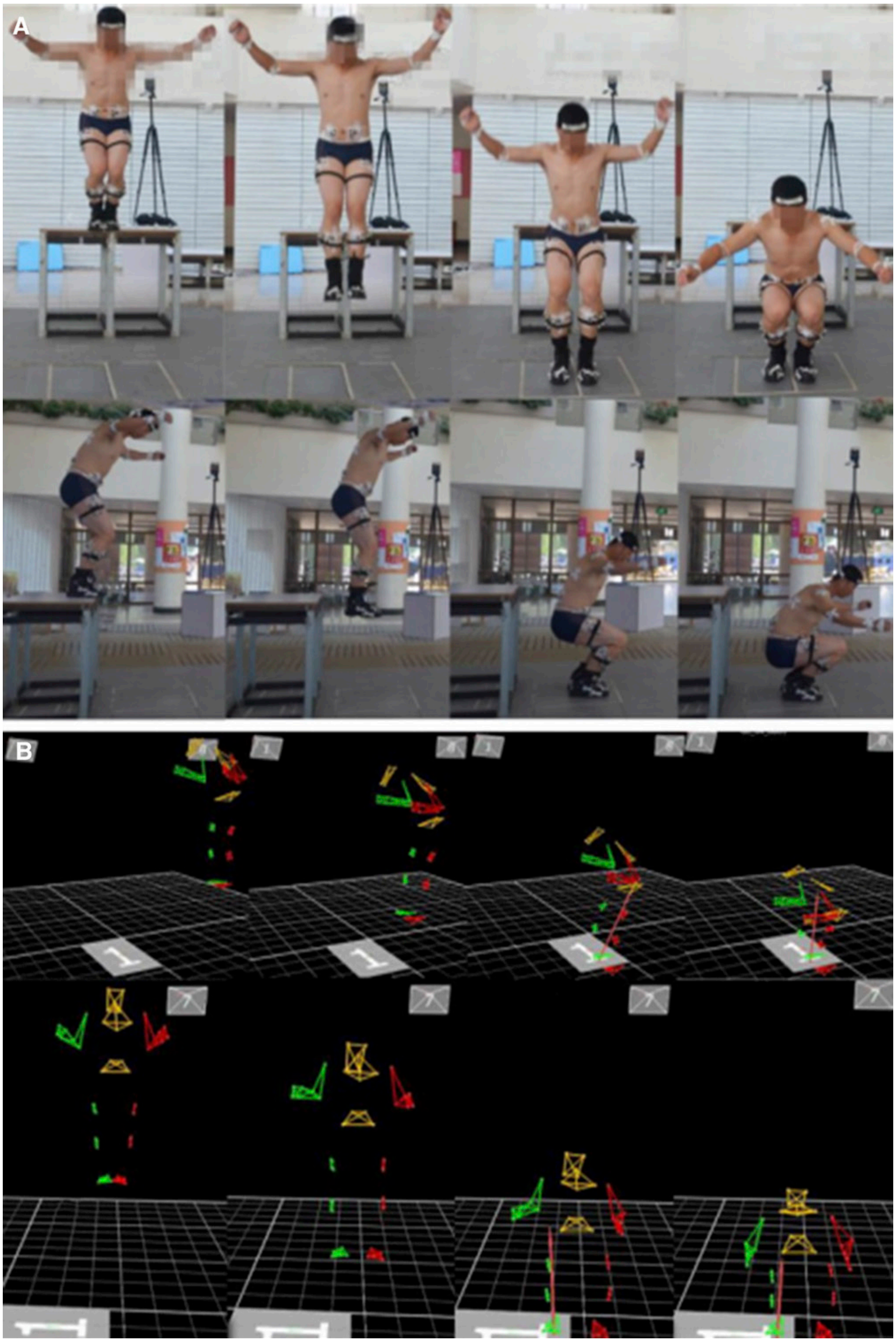

Fig. 1. A) Half-squat parachute landing. Each subject performed the half-squat parachute landing in accordance with a standard protocol. The posture of the ankle was recorded from positive and lateral sides during the stages of preparation, while in the air, and while landing on the force plate. B) Virtual parachute procedure. Vicon 3D software was used to upload raw data for further processing, complement missing or incomplete dots, and confirm a fluent and integrated parachute landing procedure by tracking movement at every time point. Please see the online version of the article for color (https://doi.org/10.3357/AMHP.4950.2018).

sample frequency of 200 Hz. Positions of the bony landmarks were determined as virtual dots with the reflective markers. All bony landmarks were defined as a visual 3D model and analyzed with the Vicon Nexus 2.1.1 software (C-Motion Inc., Germantown, MD), which was used to compute 3D kinematic variables of the dominant lower extremity (**Fig. 1B**). The maximal angular displacement, maximal angular velocity, and the time to maximal dorsiflexion angle were calculated with the software. All the subjects were asked the same questions briefly after participation: 1) what extent do you consider the braces can protect your ankles from injury? 2) How about the comfort of the braces? 3) Do you like the design and appearance of the braces? 4) Whether the brace will affect the mobility of the ankles during the test or not? At the same time, they all completed the self-designed scoring sheet according to the degree of satisfaction.

Statistical Analyses

The control variables established for the study were dropping heights (two levels: 0.4 m and 0.8 m) and conditions (no-brace, elastic ankle brace, semirigid ankle brace). Two-way analysis of variance was used to determine the significance of all variables between the two dropping heights under all three conditions. If an interaction existed, the least significant difference was used to determine significance between the brace and no brace conditions at each height. When no interactions were present, the main effect of the braces was analyzed. A probability (*P*) value of < 0.05 was considered statistically significant. All statistical analyses were performed using SPSS software for Windows, version 20.0 (IBM Corp., Armonk, NY).

RESULTS

According the satisfaction scores, of all paratroopers participating in this experiment, 70% thought that the comfort of the semirigid ankle brace was poor, the material was too hard, and the edge was too sharp. Overall, the comfort was not better than that of the elastic ankle support

[4.47 ± 0.51 vs. 2.40 ± 0.62, $F(1,59) = 199.064$, $P < 0.001$]. The participants were all satisfied with the design and appearance of the two braces [4.50 ± 0.51 vs. 4.60 ± 0.50, $F(1,59) = 0.592$, $P = 0.445$], while they held the views that the semirigid brace had a more protective effect on the ankle [3.70 ± 0.65 vs. 4.40 ± 0.50, $F(1,59) = 21.862$, $P < 0.001$] and limited the mobility of the ankle joint more effectively than the elastic brace [4.60 ± 0.50 vs. 4.07 ± 0.37, $F(1,59) = 22.361$, $P < 0.001$].

The dropping heights had a significant effect on peak vGRF ($P < 0.001$), maximum ankle angular displacements of dorsiflexion and inversion ($P < 0.001$), and time to peak vGRF ($P < 0.001$). However, maximal angular velocity of dorsiflexion (0.4 m: 536.55 ± 274.81 vs. 0.8 m: 576.26 ± 300.12° · s^{-1}; $P = 0.339$) and inversion (0.4 m: 391.23 ± 335.46 vs. 0.8 m: 442.93 ± 469.46° · s^{-1}; $P = 0.354$), and time to maximal dorsiflexion angle (0.4 m: 194.75 ± 70.83 vs. 0.8 m: 219.00 ± 71.05 ms; $P = 0.381$) were not statistically significant. Compared with the no-brace condition, use of the elastic ankle brace significantly reduced peak vGRF by 18.57% ($P < 0.001$) and both braces significantly reduced the maximal angular displacement of dorsiflexion ($P < 0.001$), whereas the semirigid brace provided greater restriction against maximal angular displacement of inversion ($P < 0.001$). Other parameters among the three conditions were not statistically significant (time to peak vGRF, $P = 0.066$; time to maximal dorsiflexion angle, $P = 0.013$; maximal angular velocity of dorsiflexion, $P = 0.149$; maximal angular velocity of inversion, $P = 0.623$) (**Table I**).

In this experiment, with the increase of dropping heights, the value of peak vGRF obviously increased (0.4 m: 7.59 ± 2.82 vs. 0.8 m: 10.65 ± 3.01 BW; **Fig. 2A**), while the time to peak vGRF decreased (0.4 m: 9.46 ± 2.44 vs. 0.8 m: 7.51 ± 2.09 ms; **Fig. 2B**). It is worth mentioning that the time to peak vGRF is often very short, while the time to complete the landing process is much longer (the former was roughly 9 ms and the latter about 250 ms). In other words, the ankle joint was not dorsiflexed enough and did not have a complete buffer at peak vGRF, and the muscles could not absorb the force. The instability of the whole body during landing may result in a shorter time to peak vGRF because, when the body is unstable, the center of gravity will change from one position to another.

The maximum angular displacement of dorsiflexion and inversion reflected the movement of the ankle joint in the sagittal and coronal planes, respectively. The angular displacement of dorsiflexion increased after initial contact with the force plate, then the value gradually returned to normal once the ankle attained maximum dorsiflexion (**Fig. 2C**). This trend was more obvious at the greater height, as with the angular displacement of inversion (**Fig. 2D**).

The vGRF quickly peaked at the moment of contact with the ground, then gradually returned to the baseline level over time, while the value of peak vGRF was smaller in the elastic and semirigid ankle brace groups than in the no-brace group (**Fig. 3A**). The angular displacement of dorsiflexion gradually increased to the extremum and the maximal angular displacement of dorsiflexion in the semirigid and elastic ankle brace groups were significantly smaller than in the no-brace group (**Fig. 3B**), but there was no significant difference between the two ankle braces. The angular displacement of inversion gradually increased to a maximum value after the feet made contact with the force plate, while the value in the semirigid ankle brace group was significantly reduced (**Fig. 3C**). Thus, both braces can maintain the stability of the ankle joint in the sagittal plane and reduce the angular displacement of inversion, while only the semirigid ankle brace had a significant impact on inversion.

DISCUSSION

In countries such as China and Russia, paratroopers perform a half-squat parachute landing, which is different from the parachute landing fall widely adopted in some other countries.[1] Half-squat parachute landing is characterized by actively and deeply

Table I. Kinematics and Kinetics Parameters Affected by Heights and Ankle Braces During Parachute Landing.

	VARIABLES							
	HEIGHT = 0.4 m			HEIGHT = 0.8 m			*P*-VALUE	
PARAMETERS	NO BRACE	ELASTIC	SEMIRIGID	NO BRACE	ELASTIC	SEMIRIGID	HEIGHT	ANKLE BRACE
Peak vGRF (BW)*	7.59 (2.82)	6.51 (2.48)	7.40 (2.66)	10.65 (3.01)	9.45 (2.90)	9.98 (2.84)	< 0.001	0.002
Time to peak vGRF (ms)	9.46 (2.44)	9.94 (3.25)	8.99 (2.25)	7.51 (2.09)	8.39 (1.82)	6.87 (1.93)	< 0.001	0.066
Maximal angular displacement of dorsiflexion (°)†	18.61 (3.84)	17.10 (5.01)	15.80 (5.03)	26.86 (5.41)	22.71 (4.87)	20.94 (3.79)	< 0.001	< 0.001
Maximal angular displacement of inversion (°)‡	7.20 (2.93)	6.86 (3.05)	4.63 (2.37)	11.43 (3.34)	10.04 (3.29)	6.83 (2.41)	< 0.001	< 0.001
Time to maximal dorsiflexion angle (ms)	194.75 (70.83)	257.50 (76.61)	232.00 (75.54)	219.00 (71.05)	257.50 (87.02)	244.50 (81.70)	0.381	0.013
Maximal angular velocity of dorsiflexion (° · s^{-1})	536.55 (274.81)	482.06 (203.30)	429.57 (119.09)	576.26 (300.12)	517.19 (288.70)	477.76 (155.03)	0.339	0.149
Maximal angular velocity of inversion (° · s^{-1})	391.23 (335.46)	302.79 (233.86)	343.22 (326.94)	442.93 (469.46)	434.86 (397.50)	339.22 (304.11)	0.354	0.623

Standard deviations are indicated in parentheses; vGRF: vertical ground reaction forces; BW: bodyweight.
* Significant differences between the no-brace and elastic groups ($P < 0.05$).
† Compared with the no-brace group, the elastic group and semirigid group had significant differences ($P < 0.05$); there was no significant difference between the elastic and semirigid groups ($P > 0.05$).
‡ Significant differences between the no-brace and semirigid groups ($P < 0.05$).

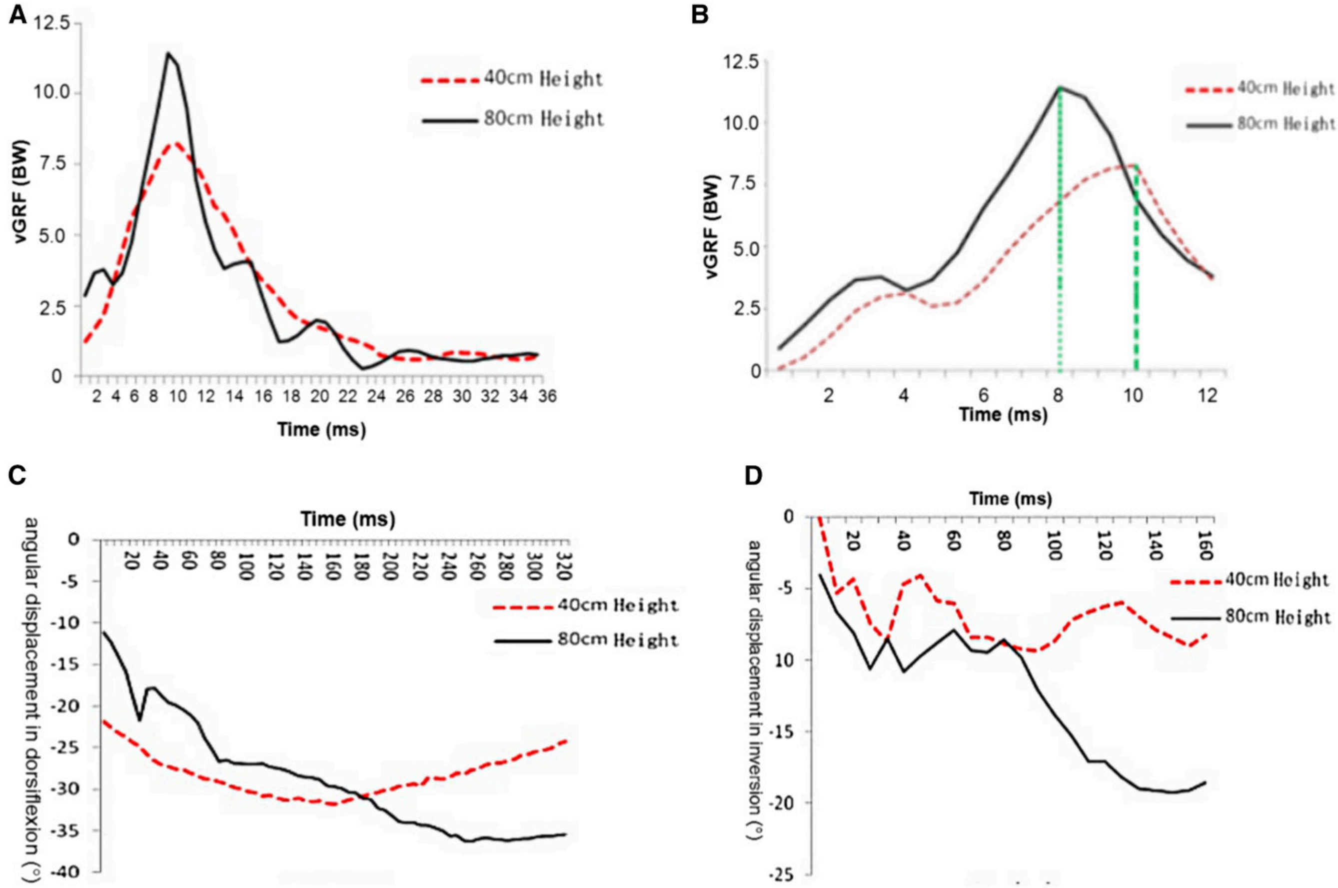

Fig. 2. Curves of kinematics and kinetics variables during half-squat parachute landing at different heights without any brace. A) Time-dependent curves of vGRF. B) Time to the peak vGRF. C) Time-dependent curves of ankle angular displacement in dorsiflexion. D) Time-dependent curves of ankle angular displacement in inversion. Please see the online version of the article for color (https://doi.org/10.3357/AMHP.4950.2018).

flexing the lower-extremity joints after the initial contact, thereby prolonging the absorption of the impact by the body segments and preventing potential injury. In the Chinese Air Force, paratroopers are taught to land with knees, ankles, and forefeet hugging each other, with the plantar parallel to the ground, which moves the center of mass forward and causes the vertical center of mass to pass through the metatarsal region.[5] When compared with the sideways roll parachute landing fall, the method of half-squat parachute landing may reduce the probability of asynchronous landing on either the left or right foot; thus it is still accepted in some countries as the only military parachute landing technique. This may seem a strange posture to westerners, but it certainly has had a long history in the Russian Air Force. Based on an epidemiological survey of the Chinese Air Force, the types of injury and the injury rates during half-squat parachute landing were similar to those during parachute landing fall.

A large peak vGRF is the fundamental cause of ankle injury in parachute landing.[7] Yeow et al. revealed that peak vGRF had an exponential relationship with landing height and that the exponential increase in peak vGRF may synergistically result in exacerbation of ankle injury risk at large landing heights.[7] Niu et al. also suggested a linear relationship between peak vGRF and dropping height.[7] With an increase in dropping height, the maximal angular velocity of dorsiflexion and inversion, and time to maximal dorsiflexion angle were all not statistically significant. The time from the initial contact with the force plate to the maximum angle of dorsiflexion is the effective time for buffering of the ankle joint. The larger the maximal angular velocity, the more kinetic energy to the ankle and the greater the risk of injury. The dorsiflexion and inversion reflected the motion stability of the ankle joint in the sagittal and coronal planes, respectively, and they cooperatively represented the kinetic energy to the ankle joint. Therefore, it is speculated that excessive dorsiflexion and inversion can lead to injury of the medial collateral ligament of the ankle joint, as well as lateral and medial malleoli fracture during parachute landing. As safety is a top priority, the heights of the platform used in this experiment do not represent the type of dropping height that causes injuries during parachute landing; when the dropping height of the parachute training exceeded 1.2 m, the lower extremities were more likely to be injuried.[6]

In this experiment, the elastic ankle brace and semirigid ankle brace both reduced the peak vGRF, with the former decreasing vGRF by 18.57% and the latter by 5.39%, while only the elastic brace had a significant effect. Theoretically, the biomechanical purpose of an ankle brace is to externally augment the ligamentous complex from the outside and limit inversion and eversion beyond the normal range of motion. At the same time, the normal movement of the ankle joint in the coronal and sagittal

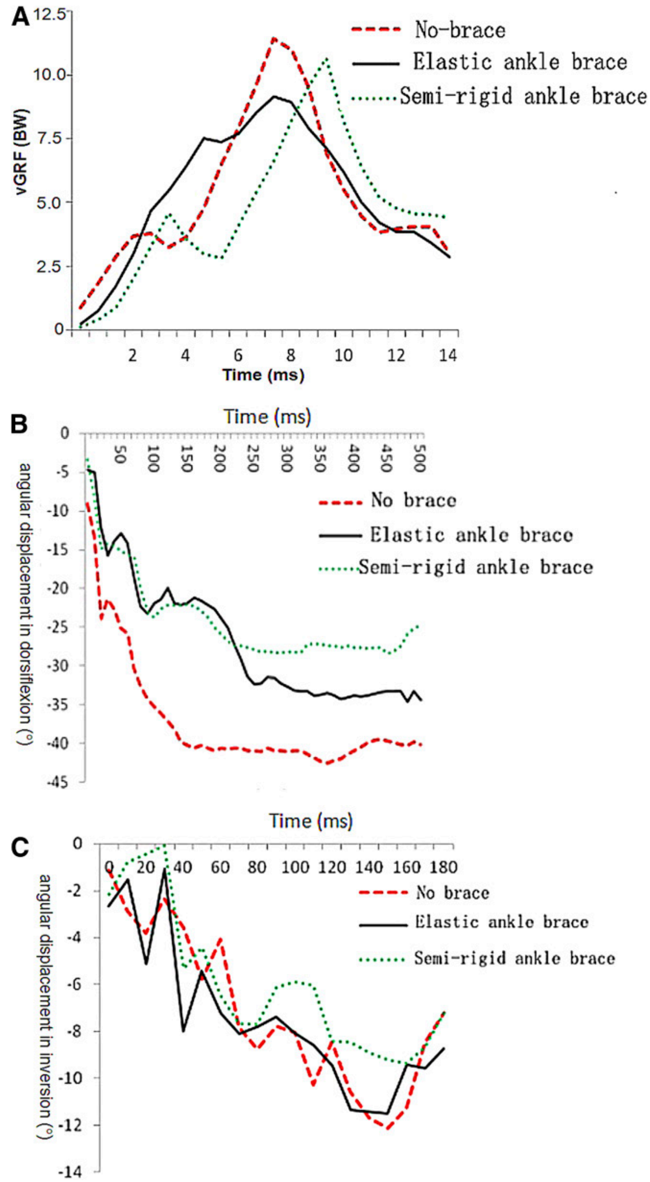

Fig. 3. Curves of kinematics and kinetics variables during half-squat parachute landing under different conditions at a height of 0.8 m. A) Time-dependent curves of vGRF. B) Time-dependent curves of ankle angular displacement in dorsiflexion. C) Time-dependent curves of ankle angular displacement in inversion. Please see the online version of the article for color (https://doi.org/10.3357/AMHP.4950.2018).

planes will not be restricted as much, so that the brace not only protects the ankle ligaments, but also has no influence on the inherent function of the ankle. This finding in our experiment was consistent with that of a study by Vanwanseele et al.,[8] who reported that the semirigid materials in the bilateral sides protecting the ankle joint afforded greater restriction of inversion and eversion. However, the application of ankle braces had no significant effect on the maximum angular velocity of dorsiflexion and inversion, although the semirigid and elastic ankle braces both decreased the angular velocity, suggesting that the two ankle braces can generally reduce the kinetic energy of the ankle joint, thereby reducing the risk of ankle injuries.

The results of this experiment were not similar with the outcomes of previous studies, possibly because the subjects were actual paratroopers rather than volunteers or athletes. The subjects in the present study performed a standard half-squat parachute landing, with the bilateral knees, medial malleoli, and the first digits of the feet always hugged together, which differs from ordinary drop and jump landings, and explained why none of the subjects landed in eversion. Hence, further studies are needed to determine whether the use of an ankle brace increased the risk of lower extremity injuries or exclusively protected the ankle.

In conclusion, an increased dropping height resulted in a greater vGRF during parachute landing. Use of the elastic ankle brace reduced the peak vGRF more effectively than with the semirigid ankle brace. The semirigid brace had the greatest reduction in inversion range of motion, but was uncomfortable. In contrast, the elastic brace was less effective at reducing the kinematics previously associated with ankle joint injury, but was more effective at reducing vGRF and was reportedly more comfortable.

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