Protective Knee Braces and the Biomechanics of the Half-Squat Parachute Landing

Di Wu; Chao Zheng; Ji Wu; Longfeng Wang; Xiang Wei; Lizheng Wang

INTRODUCTION: Knee injuries are common among paratroopers and skydivers during landing maneuvers. The aim of this study was to investigate the effects of dropping height and the use of protective knee braces on parachute landing biomechanics.

METHODS: The study cohort consisted of 30 male elite paratroopers with formal parachute landing training and more than 2 yr of parachute jumping experience. Each participant was instructed to jump off a platform at two different heights (40 and 80 cm, respectively) and land on force plates in a half-squat posture. All participants tested three different knee brace conditions (no-brace, elastic brace, and semi-rigid brace) at each height.

RESULTS: With an increase in dropping height, peak vertical ground reaction forces (GRF), peak flexion angle, peak flexion angular displacement, peak abduction angle, peak abduction angular displacement, peak extorsion angle, and peak extorsion angular displacement of the knee joint all increased. As compared without the use of a brace, use of an elastic or semi-rigid knee brace significantly reduced peak flexion angle, peak flexion angular displacement, peak abduction angular displacement, and peak extorsion angle, while there were no significant differences in peak vertical GRF or peak extorsion angular displacement. The semi-rigid brace provided the greatest restriction against peak abduction angle (3–6°).

DISCUSSION: The elastic and semi-rigid knee braces both effectively restricted motion stability of the knee joint in the sagittal and coronal planes. The semi-rigid brace had a more marked effect, although the comfort of this device should be improved.

KEYWORDS: half-squat parachute landing, knee injury, knee brace, dropping height, biomechanics.

Wu D, Zheng C, Wu J, Wang L, Wei X, Wang L. *Protective knee braces and the biomechanics of the half-squat parachute landing*. Aerosp Med Hum Perform. 2018; 89(1):26–31.

Parachuting during military maneuvers and sports training is associated with a high risk of knee injury. The parachuting process basically consists of exiting the aircraft, dropping through the air, and landing on the ground. Approximately 80% of parachuting injuries occur at the moment of landing.[6] The posture of half-squat parachute landing has been adopted by Chinese paratroops. 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.[1] In this maneuver, the upper body is in a neutral stance position and the lower extremities in a half-squat position, with the legs slightly bent and extending forward. The bilateral knees, medial malleoli, and feet are kept tight, and the feet should be parallel with the ground. Half-squat parachute landing is characterized by actively and deeply flexing the lower-extremity joints after the initial contact, thereby prolonging the absorption of the impact by the body segments and preventing potential injury.[7] Ground reaction force (GRF) is about 4–6 fold greater than bodyweight (BW) and is conducted superiorly from the planta, to the shank and knee, up to the body. At the same time, muscle contraction together with joint flexion and extension are performed to buffer the body against GRF. Therefore, the knee joints are prone to damage.

An epidemiological investigation conducted by our team found that knee injuries accounted for 21.1% of parachute landing injuries, behind ankle and spinal cord injuries. The most common injury is fracture of the knee joint followed by injuries

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This manuscript was received for review in March 2017. It was accepted for publication in August 2017.

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DOI: https://doi.org/10.3357/AMHP.4887.2018

of the cruciate ligaments, collateral ligaments, and meniscus. Even more serious injuries include tears to the anterior cruciate ligament (ACL) or meniscus and intra-articular fractures.[1,2] Previous studies have asserted that an incorrect landing posture, hard uneven ground, rough wind, and poor physical condition were all risk factors of knee injury. In addition to these widely acknowledged risk factors, it remains unclear whether the half-squat parachute landing maneuver is associated with a lower risk of injury.[4] A finite element model developed by Kiapour et al. to analyze knee injury found that impact force was a direct cause of injuries to the meniscus and articular cartilage, concluding that the anterior cruciate and collateral ligaments were more easily torn at the peak knee flexion angle.[5] Other studies revealed that GRF, the inertia effect of motion of the muscles and knees in the sagittal plane, and excessive valgus and extorsion of the knee joints all promoted ACL injury. The meniscus is prone to damage during flexion of the knee to withstand an axial load, accompanied with adduction or extension.

Knee braces have a multitude of uses, including stabilization of the knee joint, prevention of injury to the knee, and as an aid during rehabilitation of the joint following injury.[9] Protective knee braces, which were initially developed to prevent knee injuries during athletic activities, may be useful to target risk factors believed to contribute to the incidence of knee injury.[8] Biomechanical studies have attempted to investigate the effects of prophylactic bracing on the incidence of knee injury, but were conducted with no conclusive understanding of high-risk dynamic activities, such as parachute landing. Few biomechanical studies have evaluated the capability of protective knee braces to reduce strain during parachute landing or to distinguish the mechanical restraint of the knee brace from the neuromuscular effects of brace wear. Unfortunately, protective knee braces are not often worn by paratroops or athletes during daily training and maneuvers. Therefore, the continued development and improvement of knee braces are greatly needed.

Bracing has been shown to increase the knee flexion angle at landing and at peak GRF during a stop-jump task, suggesting the increased shock absorption due to increase in knee range-of-motion might account for a possible reduced risk of injury. However, this association has not been extensively investigated during landing from greater heights, which directly correlates with elevated GRFs. Therefore, the objective of this study was to investigate changes in knee biomechanics with protective knee braces and to evaluate the effectiveness of elastic and semi-rigid braces to reduce knee injury during simulated half-squat parachute landing from two heights.

METHODS

Subjects

The study cohort consisted of 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; mean military parachute jumping experience, 2.80 ± 0.53 yr). All participants were healthy and met the following inclusion criteria: 1) age: 18–30 yr; height: 170–190 cm; weight: 60–80 kg; and 2) participation in formal parachuting/parachute landing training and more than 2 yr of parachuting experience. Participants were excluded from participation in the study for any of the following: 1) a history or diagnosis of ankle, knee, or hip joint trauma, or spinal fractures; 2) a history of previous surgery of the lower extremities, neurological or joint degenerative disease, or vestibular or visual disturbance; or 3) current pain or inability to perform the landing task or activities of daily living. All testing procedures were approved by the Institutional Review Board of the Air Force General Hospital of the Chinese People's Liberation Army (Beijing, China) and written informed consent was obtained from all participants before the experiment. The study was performed in the biomechanical laboratory of Beihang University (Beijing, China).

Equipment and Materials

Two commercially available types of knee stabilizers were used in this experiment: an elastic knee brace (LP631, Puma Ltd., Taiwan, China), composed of 58% nylon, 34% rubber, and 8% polyester, which is wrapped around the knee to provide a soft cushion to the knee ligament; and a semi-rigid knee brace (LP758, Puma Ltd), composed of 75% synthetic rubber and 25% drawing nylon, with two semi-rigid steel bars that function as medial and lateral ligaments to provide increased stability to the medial and lateral collateral ligaments.

Procedure

Before testing, reflective markers (9.5 mm diameter) were placed at specific anatomical landmarks, which were used to determine the three-dimensional (3D) motion of the whole body. Before jumping, each participant jogged for 5 min at a comfortable speed as a standardized warm-up, and then was instructed to perform a half-squat parachute landing maneuver by jumping off the platform at two different heights (40 and 80 cm, respectively) and landing onto a force plate (SMA-6; AMTI, Watertown, MA) with the dominant leg, defined as the leg which one would use to kick a ball as far as possible. The bilateral hips, knees, and ankles were kept flexed until the trunk regained balance and resumed a neutral stance position.[7] Each participant was evaluated under three different knee brace conditions (no-brace, elastic knee brace, and semi-rigid knee brace), respectively. The participant was allowed to practice the maneuver and the test protocol in five trials under each condition at each height. A trial was considered successful if the participant started and terminated the drop landing movement in a standing position, jumped off and touched down with both feet, and smoothly stopped the fall in a half-squat position. The order of the experimental conditions 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. Kinematic data were collected at 200 Hz using a 3D motion capture system (Vicon; Oxford Metrics Ltd., Oxford, UK). The entire simulated parachute jump in a half-squat posture was recorded with a system consisting of eight optical infrared cameras (MX-T 40S, Vicon; Oxford Metrics Ltd.) positioned around the laboratory. GRF was simultaneously collected at 1500 Hz using two synchronized AMTI force plates embedded into the floor. The force plates were covered with rubber mats to provide similar surface properties to avoid any potential imbalance. All the subjects were required to describe the comfort of both ankle braces (good or poor) briefly after participation.

Statistical Analysis

Markers were labeled using Vicon Nexus 2.1.1 software (Oxford Metrics Ltd.) and any blank marker trajectories existing between subsequent time frames were filled by dot interpolation. Finally, the data were imported to Visual 3D gait posture analysis software (C-Motion, Inc., Germantown, MD), which was used to compute and calculate the 3D kinematic variables of the dominant leg, including peak angles and angular displacements during flexion, abduction, and extorsion. Vertical GRF data were normalized to BW and analyzed by two-way analysis of variance using SPSS v. 20.0 software (IBM-SPSS, Inc., Chicago, IL). 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.

RESULTS

All participants completed the experiment and none were injured during testing. All participants reported that the knee braces had an obvious protective effect and 60% of the participants found it difficult to distinguish the effects of the elastic knee brace from those of the semi-rigid knee brace. While 8/30 of the participants reported that the semi-rigid knee brace had a more marked protective effect, 70% stated that the comfort of this device should be improved.

When the results for the dependent variables were considered separately, there were significant differences in all dependent variables between the two heights ($P < 0.01$). Furthermore, the values of all dependent variables at a height of 80 cm were greater than that at a height of 40 cm (**Table I**). When under the condition of the same dropping height, there were no significant differences in peak vertical GRF (80 cm: 10.31 ± 1.97 vs. 9.90 ± 1.71 vs. 9.71 ± 1.53 BW; $P = 0.22$) or peak extorsion angular displacement (80 cm: 12.62 ± 5.44 vs. 11.38 ± 4.49 vs. 10.43 ± 5.31°; $P = 0.097$) with no brace, an elastic brace, and a semi-rigid brace (**Fig. 1**).

As compared to without the use of a brace, both braces significantly reduced the peak flexion angle, peak abduction angular displacement, and peak extorsion angle of the knee joint.

Table I. The Effects of Dropping Heights and Knee Braces on Knee Biomechanics During Simulated Half-Squat Parachute Landing.

GROUPS ($N = 30$)	DH = 40 cm	DH = 80 cm	HEIGHT *P*-VALUE	BRACE *P*-VALUE
Peak vertical ground reaction force (BW)				
No brace	7.48 ± 1.82	10.31 ± 1.97	$P < 0.01$	$P = 0.22$
Elastic brace	7.00 ± 1.78	9.90 ± 1.71		
Semi-rigid brace	6.74 ± 1.54	9.71 ± 1.53		
Peak flexion angle (°)†,*,¶				
No brace	107.56 ± 8.80	130.85 ± 11.08	$P < 0.01$	$P < 0.01$
Elastic brace	97.14 ± 8.51	118.64 ± 12.05		
Semi-rigid brace	93.66 ± 8.45	115.05 ± 8.74		
Peak flexion angular displacement (°)†,*,§				
No brace	76.21 ± 9.2	95.67 ± 13.4	$P < 0.01$	$P < 0.01$
Elastic brace	65.18 ± 11.6	86.09 ± 12.0		
Semi-rigid brace	59.13 ± 13.3	80.04 ± 10.7		
Peak abduction angle (°) ††,*,§				
No brace	12.52 ± 2.5	14.20 ± 1.88	$P < 0.01$	$P < 0.01$
Elastic brace	11.27 ± 1.78	13.81 ± 1.90		
Semi-rigid brace	9.71 ± 2.23	11.38 ± 2.35		
Peak abduction angular displacement (°)†,*,¶				
No brace	13.72 ± 4.08	17.35 ± 4.04	$P < 0.01$	$P < 0.01$
Elastic brace	9.60 ± 4.47	13.18 ± 3.38		
Semi-rigid brace	8.70 ± 3.28	11.45 ± 3.11		
Peak extorsion angle (°)†,*				
No brace	10.01 ± 1.33	12.93 ± 2.91	$P < 0.01$	$P < 0.01$
Elastic brace	8.82 ± 1.36	10.47 ± 1.79		
Semi-rigid brace	8.99 ± 2.06	10.41 ± 3.19		
Peak extorsion angular displacement (°)				
No brace	9.68 ± 2.43	12.62 ± 5.44	$P < 0.01$	$P = 0.097$
Elastic brace	7.97 ± 2.28	11.38 ± 4.49		
Semi-rigid brace	8.14 ± 3.14	1403 ± 5.31		

Values are presented as mean ± SD. DH = dropping height; BW = bodyweight.

† Compared with the no brace group, the elastic knee brace had significant difference ($P < 0.05$).

†† There was no statistical difference between the no brace group and elastic knee brace group ($P > 0.05$).

* Compared with the no brace group, the semi-rigid knee brace had significant difference ($P < 0.05$).

§ Compared with the elastic knee brace group, the semi-rigid knee brace had a significant difference ($P < 0.05$).

¶ There was no significant difference between the elastic knee brace and the semi-rigid knee brace ($P > 0.05$).

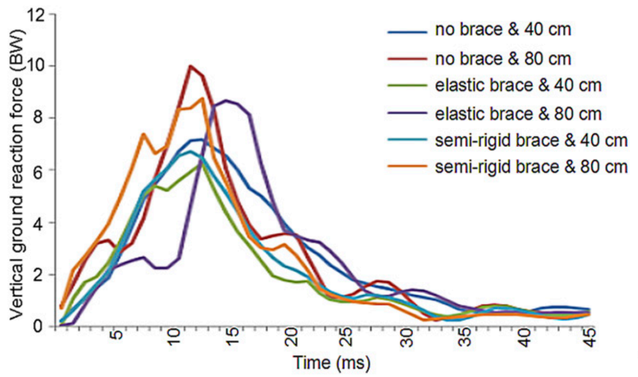

Fig. 1. Time-dependent curves of vertical GRF under different conditions during half-squat parachute landing at different heights (see the online version of this article for color).

For these dependent variables, there were no significant statistical differences between the elastic and semi-rigid knee braces (peak flexion angle, $P = 0.103$; peak abduction angular displacement, $P = 0.19$; peak extorsion angle, $P = 0.91$). The semi-rigid knee brace provided greater restriction against peak abduction angle (80 cm: 14.20 ± 1.88 vs. 13.81 ± 1.90 vs. 11.38 ± 2.35°; $P < 0.01$) and peak flexion angular displacement (80 cm: 95.67 ± 13.4 vs. 86.09 ± 12.0 vs. 80.04 ± 10.7°; $P < 0.01$) than the elastic knee brace. In addition, there was no significant difference in peak abduction angle between no brace and the use of an elastic knee brace (80 cm: 14.20 ± 1.88 vs. 13.81 ± 1.90°; $P = 0.072$) (**Fig. 2**).

The elastic knee brace and semi-rigid knee brace both effectively restricted knee flexion, with the former decreasing peak flexion angle by 9% and the latter by 12.1%. Similarly, the former decreased peak flexion angular displacement by 9% and the latter by 16.4%. Thus, the semi-rigid knee brace was more effective because semi-rigid steel bars are fixed on both sides of the semi-rigid knee brace, which may limit knee flexion. The semi-rigid knee brace effectively decreased the peak abduction angle and angular displacement of the knee joint by 3–6°, while the elastic knee brace reduced the peak abduction angular displacement by only about 4°, indicating that both protective devices increased the stability of the knee joint in the coronal plane, although the semi-rigid brace had a more significant effect. Both protective knee braces reduced the peak extorsion angle by only about 1.5° and had no significant effect on the peak extorsion angular displacement, suggesting that rotation of the knee joint was not obviously restricted because the width of the semi-rigid steel bar was too narrow to limit rotation of the tibia (Table I).

DISCUSSION

The purpose of this experiment was to investigate changes in knee biomechanics with protective knee braces during simulated half-squat parachute landing from two heights. The results showed that the elastic and semi-rigid knee braces both effectively restricted motion of the knee joint in the sagittal and coronal planes. Besides, there was a significant positive correlation between dropping heights and biomechanical variables (vertical GRF, flexion angle, abduction angle, etc.). The focus of many previous studies was ankle injury rather than knee joint injury during landing. The mechanism of knee injury has become an important topic in sports medicine. The 3D motion capture technology is a reliable and widely used method in the field of biomechanical study. Consistent with previous studies, the images collected with the 3D motion capture system were clear with high sampling frequency. Moreover, the data were calculated and analyzed from multiple perspectives at each time point using visual 3D gait posture analysis software.

A unique aspect of this study was that the participants were actual paratroopers rather than volunteers or athletes. Besides, the participants in the present study performed the standard half-squat parachute landing, which differs from ordinary drop and jump landings. To the best of our knowledge, the mechanism of knee injury and the application of protective equipment during parachute landing, which were investigated using a 3D motion capture system, has not been reported.

Landing from a greater height may be associated with an increased risk of injury. The results of the present study showed that the peak vertical GRF at a height of 80 cm was greater than that at a height of 40 cm. A study conducted by Ewing et al. of 15 recreational athletes (7 men and 8 women) jumping from a platform (0.30 and 0.60 m) in a half-squat landing posture found that the peak vertical GRF was 4.26 ± 2.06 BW during half squat landing from a height of 0.60 m.[3] It is likely that the physical quality and proficiency of recreational athletes are much lower than those of active-duty paratroopers, which were likely responsible for the differences in kinematic and kinetic data.

As shown in Table I, the peak knee flexion angle and angular displacement, which are the most important indices of ACL injury and knee joint stability in the sagittal plane, were both greater at a height of 80 cm than that at 40 cm, suggesting that the knee joint in the sagittal plane is more unstable at a greater dropping height. In order to prevent excessive knee flexion, the quadriceps contract and the tibia is pulled, thereby generating shear force to the anterior tibia, which causes greater loading to the ACL.[11] A study conducted by Kiapour et al. with a dynamic finite element model of the human knee concluded that when the peak knee flexion angle exceeded 130°, tension of the ACL increased rapidly.[5] Excessive abduction of the knee joint is a main factor of collateral ligament injury. At a greater dropping height, the peak abduction angle and displacement both increased, and the stability of the coronal plane decreased, as did the peak extorsion angle and displacement. Taken together, the biomechanical data indicated a positive correlation between the dropping height and knee injury; thus, protective measures may reduce injuries during parachute landings.

Previous studies have acknowledged that knee braces convey certain protective effects to the knee joint during jumping movements and maintain proprioception, stability, balance, and collaboration of the knee, thereby alleviating fatigue and preventing injury during participation in sports.[3,8,9,11] In the present study, the most common protective knee braces used by athletes (elastic

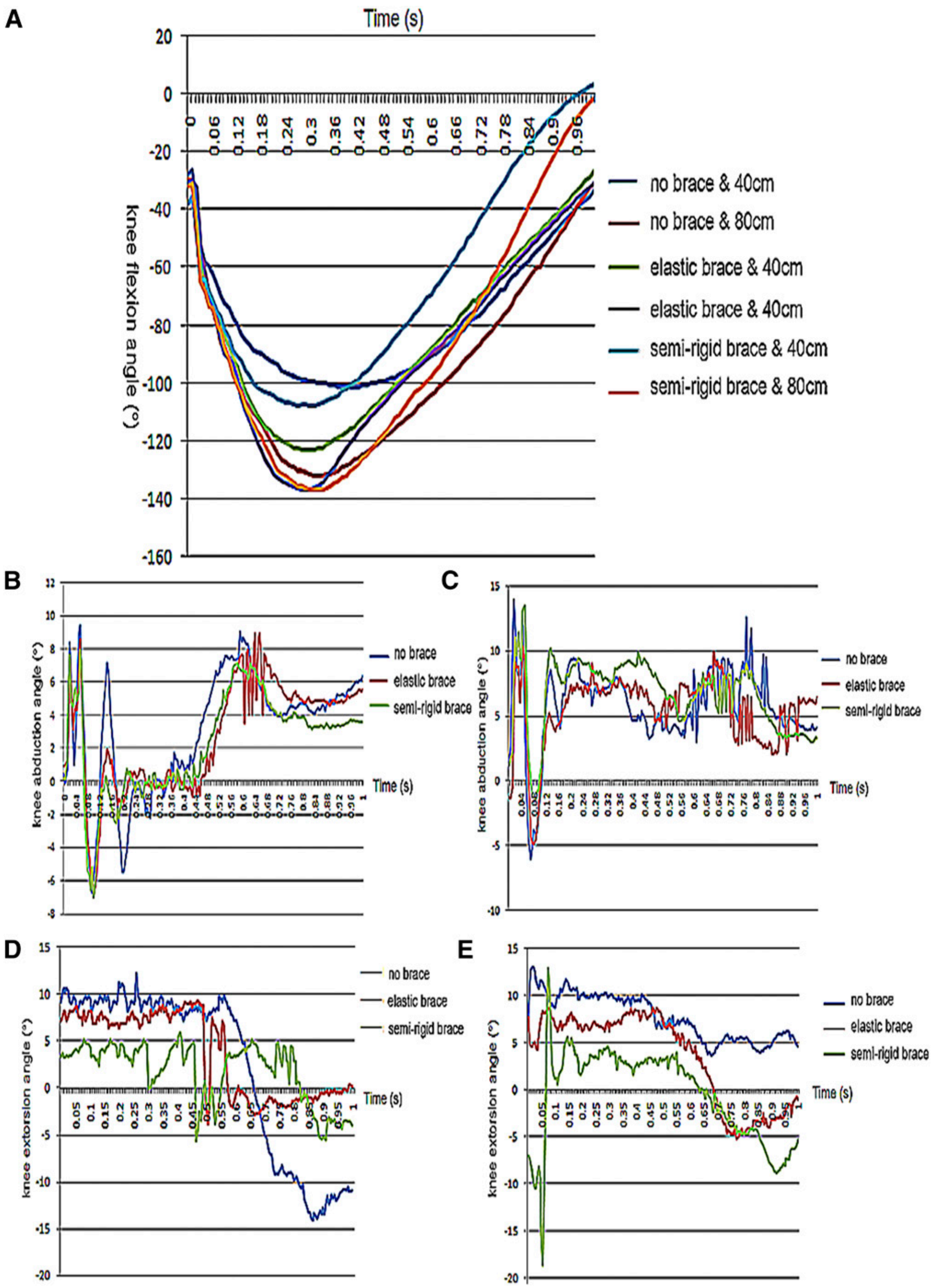

Fig. 2. Curves of kinematic variables under different conditions during half-squat parachute landing at different heights (see the online version of this article for color). A) Time-dependent curves of the knee flexion angle. B) Time-dependent curves of the knee abduction angle under different conditions at a height of 40 cm. C) Time-dependent curves of the knee abduction angle under different conditions at a height of 80 cm. D) Time-dependent curves of the knee extorsion angle under different conditions at a height of 40 cm. E) Time-dependent curves of the knee extorsion angle under different conditions at a height of 80 cm.

and semi-rigid braces) were evaluated to elucidate the protective mechanisms and to provide a first approach to design a prophylactic knee brace specifically for paratroopers and sky divers.

The use of a protective knee brace had little effect on the peak vertical GRF, as there were no significant differences in peak vertical GRF with no brace and with the use of an elastic brace or a semi-rigid brace at 40 cm and 80 cm. Rishiraj et al. suggested that the use of a knee brace can reduce vertical GRF during landing from a platform and protect the ACL from injury before the occurrence of neuromuscular functional activity.[10] The present study also found that the peak vertical GRF in the elastic brace group and semi-rigid brace group were lower than that of the no brace group, but there was no significant difference. If the number of subjects or the height of the platform was increased, a difference may gradually appear. According to the momentum theorem ($F \times t = m \times v$), GRF (F) is related to the velocity of landing (v), the BW of the subject (m), and the interaction time with the ground (t). If the use of a protective knee brace can extend the interaction time, then the peak vertical GRF is theoretically reduced, although further studies are needed to confirm this hypothesis.

This study investigated knee joint biomechanics in all three planes during simulated half-squat parachute landing. However, knee joint moments and energetics should be considered in future studies. Investigating landing biomechanics during different postures will provide a deeper understanding of the effectiveness of knee braces. In addition, possible changes in muscle contraction patterns resulting from the braces were not taken into account. An inverse dynamics approach to quantify changes in muscle activation and forces produced while wearing a knee brace should be employed as a next step. Also, future research should focus on the real-world application of these braces to determine if they have an effect on injuries.

In conclusion, an increase in dropping height resulted in a greater peak vertical GRF, which may lead to ligament damage or even fracture during parachute landing. The application of an elastic knee brace and a semi-rigid knee brace both effectively restricted motion of the knee joint in the sagittal and coronal planes. Although the semi-rigid brace had a more marked effect, the comfort of this device should be improved.

Neither of the knee braces decreased the peak vertical GRF or effectively protected the knee from extorsion.

ACKNOWLEDGMENTS

This project was supported by the key project of the army's scientific research program (BKJ14J004). 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. The authors thank Dr. Tan Hu and Dr. Linfei Wang (Air Force General Hospital of the Chinese People's Liberation Army, Beijing, China), and Dr. Tianyun Jiang (Beihang University, Beijing, China) for statistical analysis and providing the photographs. The authors also thank the reviewers for their constructive and valuable comments and suggestions.

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