# A prophylactic lumbosacral brace and the biomechanics of parachute landing

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**Background:** Lumbar injuries are common among paratroopers during landing maneuvers. Although bracing is widely advocated to increase spine stability, the effect of lumbar bracing on parachuting has yet to be quantified and the Chinese parachutist does not have a uniform prophylactic brace. The aim is to compare the effects of a novel, self-designed and self-manufactured lumbosacral brace with two ordinary lumbar braces based on biomechanical assessment of the lumbar and lower extremity joints during parachute landing.

**Methods:** The study cohort consisted of 30 elite male paratroopers. Each participant was instructed to jump off a platform at two different heights (60 and 120 cm, respectively) and land on the force plate in a half-squat posture. Participants at each height were tested under four different conditions (no brace, elastic brace, semi-rigid brace, and lumbosacral brace). The Vicon 3D motion capture system and force plate were used to record and calculate biomechanical data, such as vertical ground reaction forces (vGRFs), joint angles, moments, and energy absorption. After the experiment, every participant completed the study questionnaires.

**Results:** The increase of the jumping height raised all the parameters significantly ($P<0.01$). The use of all three braces slightly decreased vGRF, and reduced the lumbar angle, moment, and angular velocity in the sagittal plane. The use of lumbosacral and semi-rigid braces restricted lumbar flexion more efficiently ($P<0.05$), and significantly increased the energy absorption of the hip joints ($P<0.01$) and hip flexion ($P<0.01$) at 120 cm. No significant effect of braces was found on the motion of knee and ankle joints. The subjective scores suggested that the lumbosacral brace was softer and more comfortable than the semi-rigid brace, and more effective than the elastic brace.

**Conclusions:** The lumbosacral brace markedly restricted the lumbar motion in the sagittal plane than the elastic brace and was more comfortable than the semi-rigid brace. Therefore, the innovative design, high efficiency, and comfortable landing of the lumbosacral brace represent a reliable option for parachute jumping and training.

**Keywords:** Lumbosacral brace; parachute landing; jumping height; biomechanical assessment; subjective score

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## Introduction

Parachuting is regarded as an important means in modern warfare, and parachuting injuries are formally recognized in the World Health Organization's International Classification of Diseases (1). Various factors are associated with parachuting injuries, such as improper landing posture, high wind speed, night parachuting, loading, unprotective equipment, and aircraft exit (2,3). More than 80% of parachute landing injuries involve lower extremities and spine, resulting in ankle sprain, knee injury and lower back pain (4). During parachute landing by Chinese military personnel, the upper body is in a neutral stance and the lower extremities are in a half-squat position, with the legs slightly bent and extended forward. In the ideal position, the inside of the knee joint, the medial malleolus and the inside of the feet are close together, and the sole is parallel to the ground (5,6). In contrast to the sideway roll and static line parachute landing adopted by most other countries, the active and deeply flexion of the lower extremity joints after initial contact by Chinese military paratroopers prolong the impact and energy absorption by the body and prevent potential injury (7,8).

### Highlight box

**Key findings**

- A novel, military issue parachute lumbosacral brace was designed and prepared according to the biomechanical characteristics of lumbar motion and risk factors of injury during paratroopers' jumping and landing.

**What is known and what is new?**

- Although bracing is a widely advocated method of increasing spine stability, the influence of lumbar bracing on parachuting has not been quantified and the Chinese parachutist does not have a uniform prophylactic brace.
- The lumbosacral brace more markedly restricted the motion of the lumbar on the sagittal plane when compared with the elastic brace and was reported to be much more comfortable than the semi-rigid brace.

**What is the implication, and what should change now?**

- The lumbosacral brace has the advantages of an innovative design, high efficiency, and superior comfort, providing a promising choice for parachute jumping and training.

Since injuries associated with lower extremity joints (i.e., hip, knee, and ankle) and spine are more common during parachute landing, studies evaluating injury and its prevention are important for paratroopers (9,10). The ability to control the lower extremities upon landing is largely dependent on the motion of the lumbar spine (11). In China, an epidemiological study reported that 454 out of 1,675 parachutists suffered ankle injuries during parachute jumping, and 922 out of 4,081 parachutists experienced similar injuries during training. Knee injuries accounted for a further 21.1% of injuries. Among the 110 parachuting injuries involving military personnel reported by Ball *et al.* (12), low back pain accounted for 7.3%, and spinal fractures occurred in 5.5% (involving lumbar spine in 2 cases, cervical spine in 1 case, and thoracic spine in 3 cases). Epstein *et al.* (13) reported that the spinal injury rate of paratroopers during parachuting was 18.5%, with lumbar spinal injury accounting for 51.4% of them. Unfortunately, protective devices are not often worn by paratroopers during daily training and maneuvers (14). Previous studies have shown sacroiliac joint bracing alters muscle activation patterns and increases the speed of movement in healthy subjects performing landing tasks, but the extent remains unclear (15,16). Our previous studies evaluated knee and ankle injury prevention via biomechanical analysis. The results suggested that wearing ankle and knee braces reduced injuries by regulating the motion of lower extremity joints, especially in the sagittal plane (5,6,17). Similarly, the U.S. Army Center recommended the use of "semi-rigid" braces during airborne operations (18). Few biomechanical studies have focused on the evaluation of lumbar and hip injuries; only one study focused specifically on the effects of the use of lumbar supports on military performance (19).

A wide variety of lumbar supports are available: flexible or rigid, under or over clothing, with or without shoulder straps (20). The key role of lumbosacral braces is to correct deformity, limit spinal motion, stabilize the spine, and reduce mechanical load (21). The protective performance of the lumbosacral brace depends not only on its material, structure, and application mode but also on its protective effect on the lumbar biomechanics (22,23). Furthermore, the effect of lumbosacral brace on the force and motion of lumbar spine and hip joints during parachute landing is unclear. Sovelius *et al.* reported that the use of lumbar support reduced lower back muscle strain and in-flight symptoms in fighter pilots (24). Campbell *et al.* hypothesized that lumbar supports decreased back muscle force by reducing the electrical activity of back muscles or increasing intra-abdominal pressure, thereby changing the motion of the lower extremities (25).

Due to limited experimental biomechanical and theoretical data, no uniform prophylactic lumbosacral brace is available for parachute jumping and training. Based on the epidemiological study of the spine and lower extremity injury during parachute landing, we developed a novel self-designed and self-made prophylactic lumbosacral brace, which was compared with an elastic lumbar brace and a semi-rigid lumbar brace during biomechanical assessments of the spine and lower extremities during parachute landings. These assessments were based on the results of kinetics, kinematics, energy parameters, and a comparative analysis of subjective scores. Our aim is to provide guidance for the prevention of parachuting injuries and a theoretical basis for the design of lumbosacral protection. We present this article in accordance with the MDAR reporting checklist (available at https://atm.amegroups.com/article/view/10.21037/atm-22-2793/rc).

## Methods

### Participants

Thirty healthy male elite paratroopers with mean age, height, and weight [± standard deviation (SD)] of 22.6 (±3.8) years, 174.3 (±6.4) cm, and 62.4 (±5.0) kg, respectively. All participants had formal parachute landing training, over 1.5 years of parachute jumping experience, without any history of musculoskeletal injury, spinal disease, or previous surgery. None of the participants performed strenuous exercise or training tasks on the day before the experiment. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). All participants were informed of the aims and protocols of this experiment and each person provided written informed consent. The study protocol was approved by the Institutional Review Board of the Air Force Medical Center of the Chinese People's Liberation Army (Beijing, China) (No. 17-06-010).

### Equipment

A three-dimensional (3D) motion capture system (200 Hz, Vicon, Oxford, UK) was utilized to obtain kinematic data. The vertical ground reaction force (vGRF) was measured with a force plate (90 cm × 60 cm × 10 cm, AMTI, Watertown, MA, USA) at the sampling frequency of 1,600 Hz. Reflective surface marker (φ =9.5 mm) sets were tightly attached to the corresponding bony landmarks. Eight cameras placed at a height of more than three meters and evenly distributed around the center of landing area, together with the camera sensors (CMOS, Vicon). The camaras were used to record the simulated parachute jumping and landing.

The lumbosacral brace and two commercial braces, an elastic lumbar brace (LP-772, LP Co., Ltd., Seattle, WA, USA) and a semi-rigid lumbar brace (LP-919, LP Co., Ltd.), were used in this experiment. The elastic lumbar brace body was composed of 75% synthetic rubber and 25% stretch nylon (*Figure 1A*). The semi-rigid lumbar brace (47% polyester, 36% rubber, 14% polyamide, and 3% elastic fiber) carried four columnar semi-rigid support bars. Two strong bands crossing from the abdomen were pressurized and fixed to strengthen the lumbar stability (*Figure 1B*).

### Fabrication of the lumbosacral brace

The body of the lumbosacral brace was composed of a porous honeycomb-like material (84% nylon and 16% spandex) called pique fabric (Uniform Hse, Hongkong, China). Acrylonitrile-butadiene-styrene (ABS) is a robust polymer with stable chemical properties and is not easily deformed. To provide basic support and pressure for the lumbar region, two ABS plates were embedded in the back of the lumbosacral protective device, each measuring 20 cm in length, 2.5 cm in width, and 0.3 cm in thickness (*Figure 1C*). Another notable feature was the buttock pad, which acted as an extension of the lumbar brace. When the parachutist fell on the ground, the buttock pad resisted the impulsive force and increased the comfort level. Thus, the impact load conduction was increased, and the instantaneous impact force was weakened. The lumbosacral brace is pressurized by two adhesive bands crossed at the front of the abdominal wall, which can be used to adjust the tightness and thereby strengthen the lumbar stability (*Figure 1D*). This innovative brace was granted a national patent (ZL 2017 2 1326335.8).

### Procedure

The participants jumped forward and flexed their lower

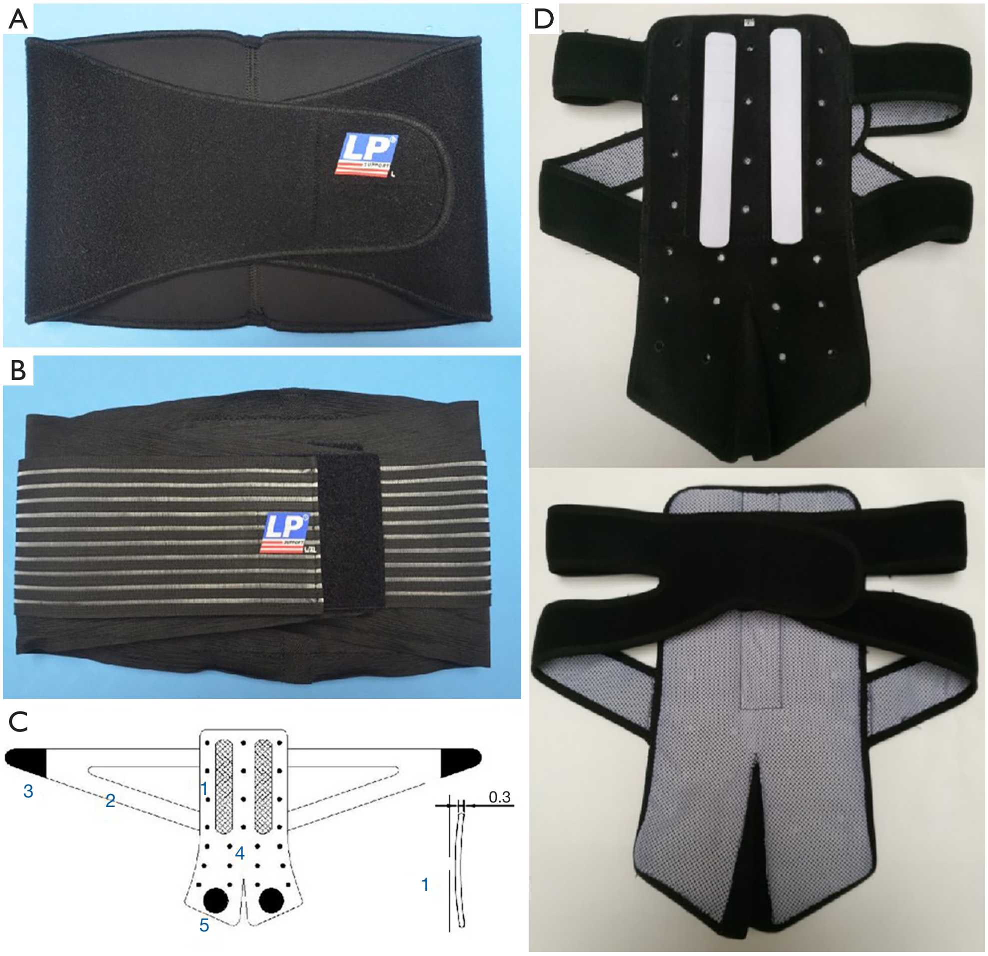


**Figure 1** Three types of braces were used in the experiment. (A) The elastic lumbar brace (LP-772, LP Co., Ltd., Seattle, WA, USA). (B) The semi-rigid lumbar brace (LP-919, LP Co., Ltd.). (C) Schematic diagram showing the lumbosacral brace structure: 1, ABS plate; 2, two strong bands; 3, adhesive strap; 4, sacrococcygeal protection; 5, buttock pad. (D) The front and back views of lumbosacral brace. ABS, acrylonitrile-butadiene-styrene.

limbs with their knees, ankles, and feet hugging each other and with the plantar parallel to the ground. This position is known as the "three hugs and one parallel" maneuver in the China Airborne School. The participants then landed on the force plate until their trunk stopped moving and resumed a neutral stance (4). The four experimental conditions were: no brace, elastic lumbar brace, semi-rigid lumbar brace, and lumbosacral brace. Participants were evaluated under four different conditions and instructed to start and terminate the 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 smoothly in a half-squat position. Each participant performed this maneuver from two different heights (low: 60 cm and high: 120 cm) in five trials under each condition. The order of the experimental conditions was random to prevent any bias. Any fatigue was alleviated by resting for at least 60 seconds between landings under each condition. A multi-rigid-body model was developed based on the static calibration of markers using the visual 3D software (Video S1).

### *Data collection and processing*

Each participant landed on the force plate, which recorded the ground reaction force (GRF) signals. GRF data were measured in the dominant foot and all vGRF values were normalized to body weight (BW). A 3D motion capture system was used to measure the 3D position of reflective markers, which determined the positions of the bony landmarks as virtual dots. All bony landmarks were defined on a visual 3D multi-rigid-body model including the spine, pelvis, and lower extremities, and then analyzed with the Vicon Nexus 2.6 software (C-Motion Inc., Germantown, MD, USA), which computed 3D kinematic variables. The AnyBody model was created for the analysis of reverse dynamics (Figure S1).

The kinetic variables included peak vGRF, peak lumbosacral moment, peak hip flexion moment, peak knee flexion moment, and peak ankle plantarflexion moment. The kinematic parameters included the maximal angle of lumbar flexion, hip flexion, knee flexion, and ankle dorsiflexion, as well as the maximal angular velocity of lumbar flexion. From a mechanical perspective, the energy absorbed by the lumbar and lower extremities refers to the amount of joint power from initial contact with the force plate to buffering completion (26). To compute the energy absorption, the joint moment was integrated over the angular displacement, which was determined via AnyBody reverse dynamics.

Following their participation in all conditions, questionnaires of three braces regarding the ease of use, quality, comfort, stability, hindrance, and satisfaction were completed by participants. The participants were also evaluated using a multiple 5-point Likert scale (27), on a scale of 1 to 5, with 1 indicating the worst and 5 representing the best outcome.

### *Statistical analysis*

Data are presented as the means ± SD. Two treatment groups were compared using Student's *t*-test. Multiple group comparisons were performed via two-way analysis of variance with Tukey's *post-hoc* test. Statistical analyses were performed using GraphPad Prism 7.0 software with P<0.05 considered to be statistically significant.

## Results

All participants completed the experiment, and none were injured during testing. According to previous research, the trunk and lower extremities were prone to instability in the sagittal plane, namely, excessive flexion (22). Therefore, this experiment mainly focused on the motion in the sagittal plane. When the results of dependent variables were analyzed separately, significant differences were found in all dependent variables between the two heights (P<0.05). Furthermore, the values of all dependent variables at a jumping height of 120 cm were greater than at 60 cm.

On average, the peak vGRF was significantly greater during the parachute landing trials performed without braces compared with trials performed with braces. Compared with the no-brace condition, the use of semi-rigid and lumbosacral braces significantly reduced the peak vGRF by 18.6% and 14.5% (P<0.01), respectively. Wearing the semi-rigid brace or lumbosacral brace decreased peak hip flexion moment (P<0.05) and peak lumbosacral moment (P<0.05), which indicated that bracing reduced hip flexion and lumbar spine kinematics during landing. No statistical difference was found in peak ankle dorsiflexion or peak knee flexion moments (*Table 1*, *Figure 2*).

As shown in *Table 2*, the maximal angle and the maximal angular velocity of lumbar flexion were decreased from 15.2°±1.9° and 267.5±36.1 °/s without a protective device at a jumping height of 60 cm to 14.1°±1.8° and 223.6±29.4 °/s (P<0.05), respectively, with the elastic brace, to 11.9°±2.2° and 195.9±27.4 °/s (P<0.01) with the semi-rigid brace, and to 13.3°±2.5° and 215.2±25.7 °/s (P<0.01) with the lumbosacral brace. These two parameters were more obvious at the jumping height of 120 cm, which indicated that the braces restricted the motion of the spine in the sagittal plane, with the semi-rigid lumbar brace providing greater restriction against lumbar flexion. The semi-rigid and lumbosacral braces effectively increased hip flexion, with the former increasing peak flexion by 9.8% and the latter by 6.5% at a jumping height of 60 cm, and by 12.1% and 10.4%, respectively, at a height of 120 cm. No significant effect of braces on the motion of knees and ankles was found, regardless of the type of brace (*Table 2*, *Figure 3*).

*Table 3* shows that increasing jumping heights significantly increased energy absorption. The joint energy absorption of the hips was increased by the braces from 1.0±0.4 BW without brace at a jumping height of 120 cm to 1.2±0.2 BW with the elastic brace, to 1.4±0.3 BW (P<0.01) with the semi-rigid brace, and to 1.4±0.2 BW (P<0.01) with the lumbosacral brace. The energy absorption of the knee and ankle joints was not significantly influenced by braces. All three braces restrict lumbar flexion during landings and maintain spine stability in the sagittal plane, with the semi-rigid brace and the lumbosacral brace associated with greater flexion limitations than the elastic brace. The increased motion of the hip joint was compensated by the reduced kinetic lumbar flexion with the braces. No statistical difference was found in the movement of ankle and knee joints with or without braces under all three

**Table 1** Effect of different jumping heights and braces on kinetics parameters (n=30)

| Variables | Heights | No brace | Elastic brace | Semi-rigid brace | Lumbosacral brace |
|---|---|---|---|---|---|
| Peak vertical ground reaction force (BW)[†,‡,§,¶] | 60 cm | 8.5±0.9 | 8.2±1.1 | 7.2±1.0 | 7.6±0.7 |
| | 120 cm | 14.5±1.2 | 13.9±1.5 | 11.8±1.8 | 12.4±1.3 |
| Peak lumbosacral moment (Nm/kg)[†,‡,§] | 60 cm | 31.8±6.2 | 29.3±4.7 | 26.4±5.5 | 27.9±6.4 |
| | 120 cm | 44.5±7.9 | 40.4±6.8 | 38.3±6.6 | 39.0±7.1 |
| Peak hip flexion moment (Nm/kg)[†,‡,§] | 60 cm | 6.7±1.0 | 7.1±1.5 | 8.2±2.1 | 7.9±1.9 |
| | 120 cm | 9.2±1.4 | 9.7±1.3 | 10.8±2.4 | 10.5± 2.2 |
| Peak knee flexion moment (Nm/kg)[†] | 60 cm | 2.3±0.9 | 2.5±0.7 | 2.6±0.8 | 2.5±0.9 |
| | 120 cm | 4.1±1.4 | 4.4±1.3 | 4.6±1.3 | 4.6±1.5 |
| Peak ankle plantarflexion moment (Nm/kg)[†] | 60 cm | 3.4±0.8 | 3.5±0.7 | 3.2±0.8 | 3.4±0.6 |
| | 120 cm | 5.0±1.1 | 4.8±0.9 | 4.7±1.0 | 4.7±1.2 |

Data are presented as the means ± SD. [†], the differences among three jumping heights are significant (P<0.05); [‡], the differences between no brace group and semi-rigid brace group are significant (P<0.05); [§], the differences between no brace group and lumbosacral brace group are significant (P<0.05); [¶], the differences between elastic brace group and semi-rigid brace group are significant (P<0.05). BW, body weight; SD, standard deviation.

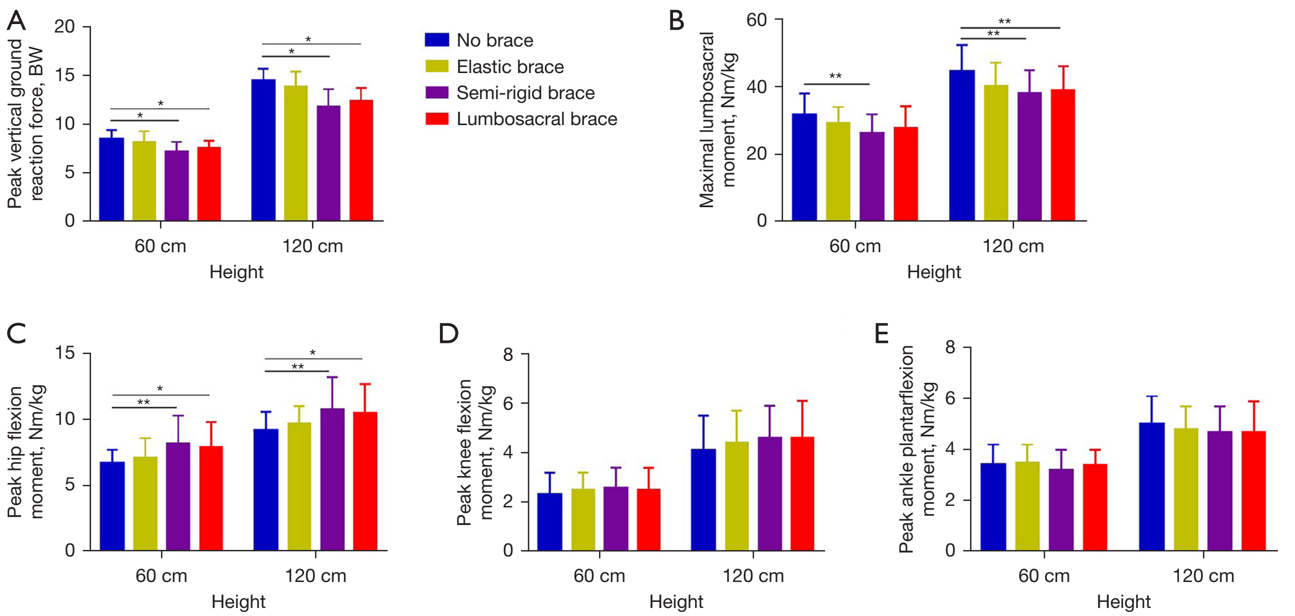


**Figure 2** Kinetic parameters affected by variation in jumping height and brace type. (A) Peak vGRF. (B) Lumbosacral moment. (C) Hip flexion moment. (D) Knee flexion moment. (E) Ankle plantarflexion moment in the sagittal plane. *, P<0.05; **, P<0.01. BW, body weight; vGRF, vertical ground reaction forces.

conditions (*Table 3*, *Figure 4*).

*Table 4* lists the subjective scores of questionnaires (i.e., perceived ease of use, quality, comfort, stability, hindrance, and overall satisfaction) completed by the participants wearing three different types of braces. The results were all statistically significant (P<0.05). The perceived quality and stability were better for the lumbosacral brace (4.1±0.4 points and 3.9±0.5 points, respectively) compared

**Table 2** Effect of different jumping heights and braces on kinematics parameters (n=30)

| Variables | Heights | No brace | Elastic brace | Semi-rigid brace | Lumbosacral brace |
|---|---|---|---|---|---|
| Maximal angle of lumbar flexion (°)†,‡,§,¶,ǀ,#,^ | 60 cm | 15.2±1.9 | 14.1±1.8 | 11.9±2.2 | 13.3±2.5 |
| | 120 cm | 32.8±2.4 | 27.7±3.0 | 20.6±2.6 | 24.2±3.1 |
| Maximal angular velocity of lumbar flexion (°/s)†,‡,§,¶,ǀ,# | 60 cm | 267.5±36.1 | 223.6±29.4 | 195.9±27.4 | 215.2±25.7 |
| | 120 cm | 382.4±40.9 | 323.6±32.6 | 282.8±30.9 | 296.9±29.8 |
| Maximal angle of hip flexion (°)†,§,¶ | 60 cm | 75.2±8.4 | 77.1±9.8 | 82.6±10.5 | 80.4±10.1 |
| | 120 cm | 90.4±10.2 | 95.3±10.7 | 101.3±11.4 | 99.8±11.9 |
| Maximal angle of knee flexion (°)† | 60 cm | 110.6±15.9 | 111.2±10.9 | 115.4±13.3 | 113.7±11.9 |
| | 120 cm | 131.2±17.6 | 129.7±16.1 | 130.8±14.5 | 130.4±15.8 |
| Maximal angle of ankle dorsiflexion (°)† | 60 cm | 22.7±4.6 | 21.8±3.9 | 21.7±4.3 | 21.8±4.1 |
| | 120 cm | 43.3±7.7 | 45.2±7.8 | 44.6±8.0 | 43.9±7.5 |

Data are presented as the means ± SD. †, the differences among three jumping heights are significant (P<0.05); ‡, the differences between the no brace group and elastic brace group are significant (P<0.05); §, the differences between the no brace group and semi-rigid brace group are significant (P<0.05); ¶, the differences between the no brace group and lumbosacral brace group are significant (P<0.05); ǀ, the differences between the elastic brace group and semi-rigid brace group are significant (P<0.05); #, the differences between the elastic brace group and lumbosacral brace group are significant (P<0.05); ^, the differences between the semi-rigid brace group and lumbosacral brace group are significant (P<0.05). SD, standard deviation.

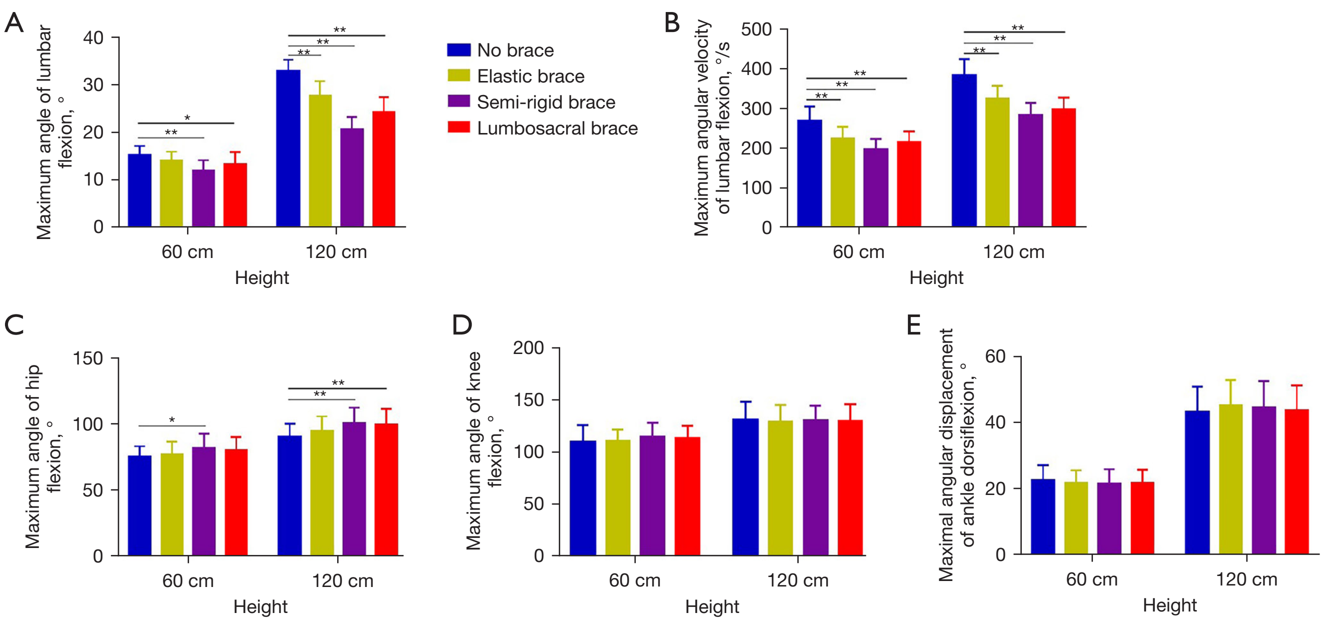


**Figure 3** Kinematic parameters affected by variation in jumping height and brace type. (A) Angle of lumbar flexion. (B) Angular velocity of lumbar flexion. (C) Angle of hip flexion. (D) Angle of knee flexion. (E) Angle of ankle dorsiflexion in the sagittal plane. *, P<0.05; **, P<0.01.

with the elastic brace (3.7±0.3 points and 3.2±0.4 points, respectively, both P<0.01). Most participants agreed that lumbosacral and semi-rigid braces restricted flexion more effectively than the elastic brace, and reported that the lumbosacral brace was softer and more comfortable than the semi-rigid brace. The lumbosacral brace was breathable due to the porous structure of the materials. Therefore, the lumbosacral brace combined the advantages of the other

 

**Table 3** Effect of different jumping heights and braces on energy absorption (n=30)

| Variables | Heights | No brace | Elastic brace | Semi-rigid brace | Lumbosacral brace |
|---|---|---|---|---|---|
| Energy absorption of hip (BW)[†,‡,§] | 60 cm | 0.6±0.1 | 0.7±0.1 | 0.6±0.2 | 0.7±0.2 |
| | 120 cm | 1.0±0.4 | 1.2±0.2 | 1.4±0.3 | 1.4±0.2 |
| Energy absorption of knee (BW)[†,¶] | 60 cm | 2.9±0.5 | 2.8±0.4 | 3.1±0.5 | 3.0±0.4 |
| | 120 cm | 4.1±0.7 | 4.5±0.8 | 3.9±0.8 | 4.2±0.5 |
| Energy absorption of ankle (BW)[†] | 60 cm | 0.7±0.2 | 0.7±0.3 | 0.6±0.2 | 0.6±0.1 |
| | 120 cm | 1.0±0.2 | 0.9±0.3 | 1.0±0.1 | 0.9±0.2 |

Data are presented as the means ± SD. [†], the differences among three jumping heights are significant (P<0.05); [‡], the differences between the no brace group and semi-rigid brace group are significant (P<0.05); [§], the differences between the no brace group and lumbosacral brace group are significant (P<0.05); [¶], the differences between the elastic brace group and lumbosacral brace group are significant (P<0.05). BW, body weight; SD, standard deviation.

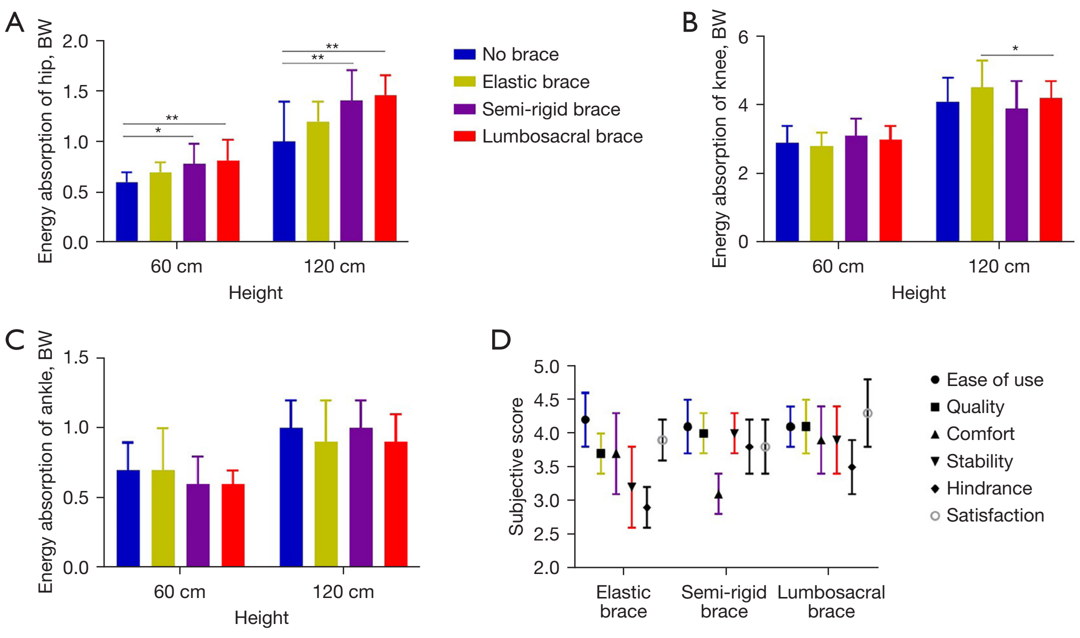


**Figure 4** Energy absorption affected by variation in jumping height and brace type, and the subjective scores. The joint energy absorption of hip (A), knee (B), and ankle (C). (D) The subjective scores of wearing different braces. *, P<0.05; **, P<0.01. BW, body weight.

**Table 4** The subjective score results of wearing different braces (n=30)

| Variables | Elastic brace | Semi-rigid brace | Lumbosacral brace |
|---|---|---|---|
| Ease of use | 4.2±0.4 | 4.1±0.4 | 4.1±0.3 |
| Quality | 3.7±0.3 | 4.0±0.3 | 4.1±0.4 |
| Comfort | 3.7±0.6 | 3.1±0.3 | 3.9±0.5 |
| Stability | 3.2±0.4 | 4.0±0.8 | 3.9±0.5 |
| Hindrance | 2.9±0.3 | 3.8±0.4 | 3.5±0.4 |
| Satisfaction | 3.9±0.3 | 3.8±0.4 | 4.3±0.5 |

Data are presented as the means ± SD. SD, standard deviation.

 

two lumbar braces, demonstrating good comfort, ease of use, high stability, and light hindrance. All the participants were satisfied with the appearance, function, and comfort of the lumbosacral brace (*Table 4*, *Figure 4*).

## Discussion

Chinese paratroopers are taught to flex their spine and land with knees, ankles, and feet hugging each other. The combination of these actions moves the center of mass forward, further prolonging the absorption of the impact and preventing potential injury (14). However, no experimental study investigated lumbar injury and protection during parachuting maneuvers. To reduce lumbar and lower extremity injuries in airborne soldiers, the current study investigated changes in the biomechanics of the lumbar, hip, knee, and ankle, and quantified the effects of a lumbosacral brace during simulated parachute jumping and landing from two heights. The lumbosacral brace was highly effective and protective during half-squat parachute landing by reducing the lumbar flexion and slightly increasing the hip flexion in the sagittal plane. The focus of many previous studies was ankle or knee injury and protection of parachutists during landing (27). Some studies reported changes in kinematics and surface electromyography of the trunk (28,29). Therefore, a lumbosacral brace suitable for Chinese paratroopers was designed and created, and the biomechanics of parachute landing was explored in this study.

The mechanism of spinal injury has become an important topic in sports medicine. The technology of 3D motion capture is reliable and widely used in the field of biomechanics due to clear images with high sampling frequency (30). To the best of our knowledge, the analysis of the mechanism of lumbar injury and the application of protective equipment during parachute landing using a 3D motion capture system has yet to be reported. We evaluated the kinetic, kinematic, and energy parameters of the lumbar, hip, knee, and ankle joints of participants with and without a brace. Lumbar lateral flexion and axial rotation rarely occurred, whereas a large degree of lumbar flexion was inevitable. Overuse injuries detected frequently among paratroopers were attributed to repetitive action, load, insufficient rest, or a combination thereof over time (31). The lumbar brace limited the range of lumbar flexion and reduced the risk of injury by lowering soft tissue tension and withstanding repeated trunk flexion (32). In this study, wearing a brace reduced the angle, angular velocity and moment of lumbar flexion, with the semi-rigid brace and lumbosacral brace showing greater effect. A large peak vGRF is the key parameter contributing to lower extremity injury in parachute landings. Niu *et al.* suggested a linear relationship between peak vGRF and dropping height (33). Our previous study also demonstrated that wearing an ankle or knee brace reduced the peak vGRF, with the former showing enhanced effect (5,6,9,17). Our study suggested that wearing a brace reduced the peak vGRF by a maximum of 18.6%. Campbell *et al.* confirmed that the lumbar support-induced changes in the kinematics of lower extremities may affect the GRF (25).

The design of a lumbosacral brace depends on its appearance, materials, and biomechanics. Elasticity of the brace enables full contact with the body and increases comfort; however, it has a relatively weak effect on limiting the range of lumbar flexion. Although the semi-rigid lumbar protection provides higher degrees of stiffness by focusing on the built-in strong support bars inside the back of the brace, it does not fit as well as the elastic brace due to the gap between the brace and back muscles. The lumbosacral brace combines the advantages of the two braces, resulting in several innovative features. A high level of security is achieved via support bar reinforcement used in the back of the lumbosacral brace, and the concave protective feature conforms to the anatomical structure of lumbar lordosis (34). The ABS plates are consistent with the anatomical contour of the lower back and effectively limited flexion. They also provide the same strength as metal support bars. Sacrococcygeal protection is achieved by the 15-fold higher reactive force than that of BW when falling and landing on the ground from a high place, especially on uneven ground (25,33). The buttock pad prolongs the buffer time, reduces the impulsive force, and changes and scatters the pressure distribution. The pique fabric (raw material) of the lumbosacral brace reduces the relative slip between the protective device and the human skin and thereby improves protection reliably, resulting in great comfort. The multiple circular holes in the surface of the brace increase its lightweight and breathability. The adhesive strap generates additional friction, and thereby prevents the risk of slippage and displacement during strenuous exercises.

A unique aspect of this study was that the participants were actual paratroopers rather than volunteers or athletes. Furthermore, the study participants performed the standard half-squat parachute landing, which differs from the ordinary drop and jump landings. Based on the established holistic synergy theory of the lower extremities and trunk (11), we explored whether the use of brace affected the energy consumption or injury to the knee and hip joints. The specially customized lumbosacral brace for parachuting is still in the preliminary stages of testing. Results suggest it can sustain external impact including a large GRF at the time of landing and continuous minor stress or strain in all directions of spine and lower extremities. Therefore, the lumbosacral brace shows promising mechanical properties, which require additional testing of shape retention, tensile strength, anti-fatigue features, fabric permeability and fabric friction.

The study has some limitations. Firstly, although other studies have demonstrated that motion was mainly changed in the sagittal plane, parametric analyses in the other two planes were not performed in this study. Secondly, the experimental design failed to simulate real-life parachute landing given the safety of participants and the general cost. Thirdly, only male participants were recruited in this experiment because the risk of injury to male paratroopers was higher than that of females (35). Finally, possible changes in muscle contraction patterns resulting from the braces were not considered. Measurement of changes in muscle activation and forces generated while wearing a lumbosacral brace is the next step. Future studies should focus on the real-world military applications of these braces to determine their impact on injuries.

## Conclusions

A novel, parachute lumbosacral brace for use by military personnel was designed and fabricated according to the biomechanical characteristics of lumbar motion and risk factors of injury during jumping and landing operations of paratroopers. Biomechanical tests showed that increasing the jumping height resulted in greater peak vGRF, kinetics, kinematics, and energy parameters, which may lead to lumbar and lower extremity injuries during parachute landings. The lumbosacral brace restricted the lumbar motion in the sagittal plane more markedly when compared with the elastic brace and was reported to be substantially more comfortable than the semi-rigid brace. Therefore, the lumbosacral brace, with innovative design, high efficiency, and superior comfort, represents a promising choice for parachute jumping and training operations.

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## Footnote

*Reporting Checklist:* The authors have completed the MDAR reporting checklist. Available at https://atm.amegroups.com/article/view/10.21037/atm-22-2793/rc

*Data Sharing Statement:* Available at https://atm.amegroups.com/article/view/10.21037/atm-22-2793/dss

*Conflicts of Interest:* All authors have completed the ICMJE uniform disclosure form (available at https://atm.amegroups.com/article/view/10.21037/atm-22-2793/coif). The authors have no conflicts of interest to declare.

*Ethical Statement:* The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Review Board of the Air Force Medical Center of the Chinese People's Liberation Army (Beijing, China) (No.17-06-010). All participants were informed of the aims and protocols of this experiment and each person provided written informed consent.



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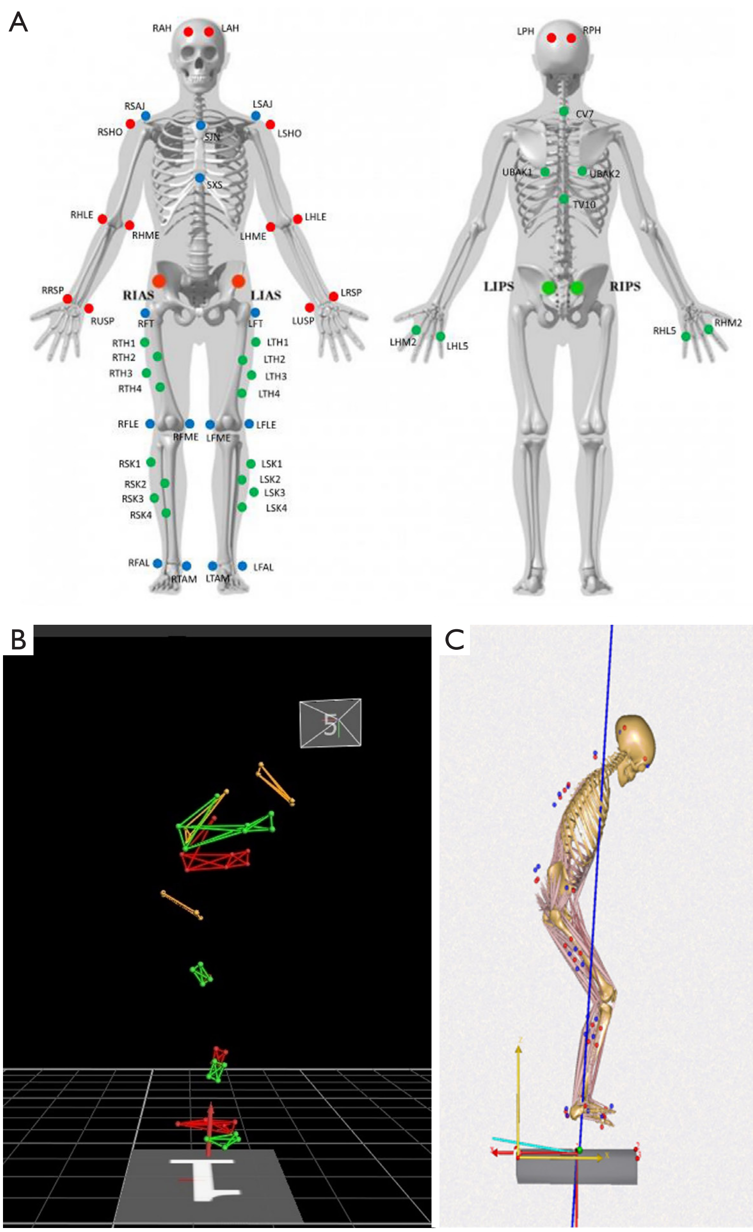


**Figure S1** The experimental procedure. (A) Reflective markers of systemic model. (B) Virtual parachute procedure. (C) The AnyBody musculoskeletal model after muscle loading. CV, cervical vertebra; LAH, left anterior head; LFAL, left fibula apex of lateral malleolus; LFLE, left femur lateral epicondyle; LFME, left femur medial epicondyle; LFT, left femur greater trochanter; LHL, left lateral head of metacarpal; LHLE, left lateral epicondyle of humerus; LHM, left head of metacarpal; LHME, left medial epicondyle of humerus; LIAS, left anterior superior iliac spine; LIPS, left posterior superior iliac spine; LPH, left posterior head; LRSP, left radius-styloid process; LSAJ, left scapula-acromioclavicular joint; LSHO, left shoulder; LSK, left shank; LTAM, left tibia apex of medial malleolus; LTH, left thigh; LUSP, left ulna-styloid process; RAH, right anterior head; RFAL, right fibula apex of lateral malleolus; RFLE, right femur lateral epicondyle; RFME, right femur medial epicondyle; RFT, right femur greater trochanter; RHL, right lateral head of metacarpal; RHLE, right lateral epicondyle of humerus; RHM, right head of metacarpal; RHME, right medial epicondyle of humerus; RIAS, right anterior superior iliac spine; RIPS, right posterior superior iliac spine; RPH, right posterior head; RRSP, right radius-styloid process; RSAJ, right scapula-acromioclavicular joint; RSHO, right shoulder; RSK, right shank; RTAM, right tibia apex of medial malleolus; RTH, right thigh; RUSP, right ulna-styloid process; SJN, sternum incisura jugularis; SXS, sternum xiphoid process; TV, thoracic vertebra; UBAK, inferior angle of scapula.

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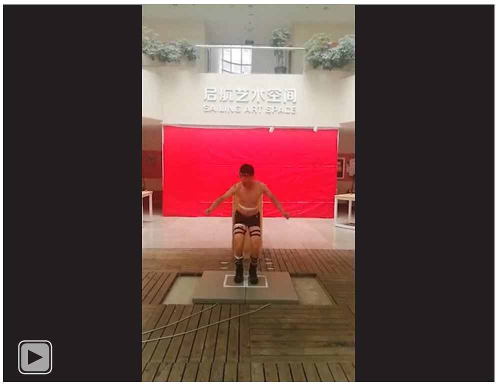


**Video S1** The participant parachuted from 120 cm and landed on the force plate in accordance with a standard protocol.

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