A novel prophylactic parachute ankle brace CPAB

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Research

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Abstract

Background: Comparing the effects of a self-designed and self-manufactured novel prophylactic ankle brace (Chinese parachute ankle brace, CPAB) and two ordinary ankle braces on the ankle joint during a half-squat parachute landing via biomechanical assessment.

Methods: Twenty elite paratroopers were in four different conditions: no brace, elastic brace, semi-rigid brace, and CPAB. Each participant was instructed to jump off a platform with three different heights, 40 cm, 80 cm, and 120 cm, and land on the AMTI force plate in a half-squat posture. The vertical ground reaction forces (vGRF), joint angles, moments, powers, and works were calculated. After the experiment, every participant completed the questionnaires designed for this study.

Result: Increasing the dropping height increased all of the parameters significantly ($P<0.01$), except for time to peak vGRF (T-PvGRF). Applying three braces can all slightly increase vGRF ($P=0.237$) and reduce T-PvGRF by 6-10 ms, as well as decrease the joint angles, velocities, and moments on the sagittal and coronal planes. Wearing CPAB and a semi-rigid brace more efficiently restricted dorsiflexion and inversion ($P<0.05$), and they both significantly reduced ankle work ($t=5.107$, $P<0.01$; $t=3.331$, $P<0.01$) and peak power ($t=7.237$, $P<0.01$; $t=6.711$, $P<0.01$) at 120 cm. The total scores from low-to-high were semi-rigid brace (19.20±2.99), elastic brace (21.91±3.25), and CPAB (23.37±3.08).

Conclusion: The CPAB was more effective at restricting ankle joint motion on the coronal and sagittal planes than the other two prophylactic ankle braces. Therefore, the CPAB had the advantages of a novel appearance, high efficiency, and superior comfort, providing a reliable choice for parachute jumping and training in China.

Background

Landing injuries are the most frequent of all parachuting injuries and ankle joint injuries are the most common landing injury [1]. The half-squat parachute landing (HSPL) posture has been adopted by Chinese paratroops [2, 3]. When compared with the sideways roll parachute landing fall, the HSPL method may reduce the probability of asynchronous landings on either the left or right foot [4]. In this maneuver, 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. Bilateral knees, medial malleoli, and feet are kept tight, and the feet should be parallel with the ground [5]. HSPL is characterized by actively and deeply flexing the joints of the lower-extremities after initial contact, thereby prolonging impact absorption by the body segments and preventing potential injury [2, 3, 5].

Ankle braces can reduce ankle injuries by 61%, while this figure increases to 79% for people with old wounds [6]. According to the application method and appearance design, available ankle braces are mainly divided into three categories: fixed slip-on, bandage winding, and bandage slip-on. Moreover, they can also be divided into the external types, internal type, and internal and external dual-use type [7]. The inconvenient external ankle brace is generally made of rigid polyethylene material, which is bulky and uncomfortable. The internal ankle brace is usually a sports product with good elasticity, but it cannot prevent excessive eversion and inversion of the ankle joint. The dual-use ankle brace is rare currently [8].

The protective performance of the ankle brace depends on not only its material, structure, and application method, but also its protective effect on the biomechanical mechanism of the ankle injury. Knapik et al. recorded 33,461 instances of parachute jumping with ankle braces and 69,323 instances of parachute jumping without ankle braces, and the results show the injury rate of the latter was 1.83-2.0 times higher than that of the former [4]. Wu et al. found that the greater the average angular velocity of inversion and dorsiflexion, the more likely it would cause ankle joint instability on the coronal and sagittal planes. They also found that elastic and semi-rigid ankle braces can significantly reduce rates of injury, but semi-rigid ankle braces are more significantly protective of excessive inversion [2]. Willeford et al. found that ankle bandages and ankle braces could significantly reduce the angular displacement of inversion, eversion, plantarflexion, and dorsiflexion of the ankle joint [9].

Despite the protection discussed above, parachute ankle brace designs lack the support of strict mechanical experimental data and a professional theoretical basis. Up to this point, no uniform prophylactic brace against ankle injury exists for when HSPL applications. In this study, a self-designed and self-manufactured novel prophylactic ankle brace (Chinese parachute ankle brace, CPAB) was developed, and it was compared with elastic ankle braces and semi-rigid ankle braces regarding biomechanical assessments of the ankle joint during HSPL, such as kinetics, kinematics, and energy parameters, as well as the comparison of subjective scores.

Methods

Subjects

Twenty elite male paratroopers (mean age, 22.56±3.76 yr; mean height, 174.32±4.58 cm; mean weight, 62.42±6.93 kg) with formal parachute landing training and over 2 yr of parachute jumping experience volunteered for this study. All eligible subjects were healthy and had 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 diseases, or vestibular or visual disturbances. 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 Peking Union Medical College Hospital, Beijing, China.

Equipment

A force plate (1600 Hz, AMTI, Watertown, MA, USA) was utilized to measure the vertical ground reaction force (vGRF). The force plate and surrounding floor had similar surface properties to avoid any potential imbalances. A 3D motion capture system (200 Hz, Vicon, Oxford, UK) was utilized to obtain kinematic data. Reflective surface marker sets were tightly attached to the corresponding bony landmarks. Eight cameras (CMOS, Vicon, Oxford, UK) containing sensors recorded the entire simulated parachute jump in a half-squat posture.

Two commercially available ankle braces and CPAB were used in this experiment: an elastic ankle brace (AQ5261EA, Tokyo, Japan) and a semi-rigid ankle brace (LP787, Seattle, WA, USA). The elastic ankle brace body was composed of an ultra-thin material, the inner shell of which was constructed of high-elastic anti-skid mesh fabric, and the outer shell was constructed of 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 ankle joint stability (Fig. 1a). The semi-rigid ankle brace contained a U-shaped semi-rigid metal spring functioning as a “hoop” at the lateral and medial malleoli (Fig. 1b).

Fabrication of CPAB

The CPAB body was composed of a sparsely porous honeycomb-like material called pique fabric (Uniform Hse, Hongkong, China). An elastic metal spring strip (tensile strength: 800 MPa; torsional strength: 28 times / 360°;

elongation: 3%) was constructed on the inner side and adapted to the anatomical outline of the medial malleolus. Also, a special aluminum strip (tensile strength: ≥370 MPa; yield strength: ≥215 MPa; elongation: ≥12%) was constructed on the outer side and adapted to the anatomical outline of the lateral malleolus. The aluminum strip was coated with cotton foam (100% ethylene-vinyl acetate copolymer) to reduce friction between the ankle joint and CPAB. The strips were the most novel part of the CPAB design, and their length was 15 cm, their width was 1.2 cm, and their thickness was 0.2cm. Another special part was the heel pad, which was made of the auxetic material with a negative Poisson ratio (polymer porous polytetrafluoroethylene). When the feet and ankle are impacted by huge ground reaction forces (GRF), the heel pad can resist excessive deformation and increase comfort. Moreover, impact load conduction is increased and instantaneous impact force is weakened. CPAB is pressurized by an adhesive band at the top and two crossed bands at the back of the foot, which users can utilize adjust the tightness and thereby strengthen the ankle joint stability (Fig. 1c-e).

Procedure

Before jumping, each subject jogged for 5 min at a comfortable speed as a warm-up, then performed the HSPL. Upon hearing the order to jump, the subject jumped forward and flexed their lower limbs with their knees, ankles, and forefeet hugging each other and with the plantar parallel to the ground. This was called “three huggings and one parallel” in the teaching material of the China Airborne School. Then they landed on the force plate until their trunk stopped moving and resumed a neutral stance [2]. Subjects were evaluated under four different ankle brace conditions (no brace, elastic ankle brace, semi-rigid ankle brace, and CPAB) 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 smoothly in a half-squat position. Each subject performed this maneuver from three different heights (low: 40 cm, medium: 80 cm, and high: 120 cm), undergoing five trials under each condition. The experimental condition order 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.

Each subject landed on the force plate, which collected GRF signals. A 3D motion capture system was utilized to measure the 3D position of reflective markers in a global reference frame. Reflective markers were utilized to determine the positions of the bony landmarks as virtual dots. All bony landmarks were defined as a visual 3D model and analyzed with the Vicon Nexus 2.6 software (C-Motion Inc., Germantown, MD, USA), which was utilized to compute 3D kinematic variables, and the AnyBody model was built to conduct reverse dynamics analysis. All subjects were briefly asked the same questions after participation, including questions regarding ease of use, quality, comfort, stability, hindrance, and satisfaction. The multiple 5-point Likert scale was evaluated by the subjects with 5 being the best and 1 being the worst.

Data Collection and Statistical Analysis

(1) The kinetic parameters: GRF data were measured in the dominant foot. All vGRF values were normalized to body weight (BW) and the time to peak vGRF (T-PvGRF) started from initial contact with the force plate. The reverse dynamic variables included the maximal plantarflexion moment (MPM) and maximal eversion moment (MEM). (2) The kinematics parameters: angular displacement of maximal dorsiflexion (MDAD), the angular displacement of maximal inversion (MIAD), the angular velocity of maximal dorsiflexion (MDAV), and angular velocity of maximal inversion (MIAV), were calculated with the software (3). The energy parameters: the work and maximum power. From the mechanics perspective, the work refers to the amount of joint power conducted in a certain period time [10], and the calculation formula is as follows:

$$\text{Work} = \int_{t2}^{t1} P(t) \bullet dt$$

P represents joint power, and t_1 and t_2 represent the start and end time points. The work done by the ankle joint from initial contact with the force plate to buffering completion is negative work, namely energy absorption. Joint power = angular velocity × joint moment, which can be obtained by Anybody reverse dynamics analysis. In this study, dorsiflexion and inversion were stipulated to be positive, while plantarflexion and eversion were negative.

Data are representative of these experiments and are shown as the means ± standard deviation (SD). Two treatment groups were compared via the t-test of Students. Multiple group comparisons were performed via a two-way analysis of variance with Tukey's post hoc test. Statistical analysis was conducted using GraphPad Prism 7.0 software, and statistical significance was declared as $P < 0.05$.

Results

All participants completed the experiment and none were injured during testing. According to previous research, ankle joints were prone to instability on the coronal and sagittal planes, namely, excessive inversion or dorsiflexion. During HSPL, the subject always maintained standard posture (the feet and medial malleoli hugged together), and feet were parallel to the ground when landing, so excessive eversion and plantarflexion would not occur. Therefore, this experiment mainly focused on inversion and dorsiflexion.

The assessment of kinetic parameters

Table 1 shows that increasing heights significantly increased peak vGRF, MPM, and MEM ($P<0.01$), while T-PvGRF significantly decreased ($P<0.01$) and T-PvGRF gradually became smaller. The time to peak vGRF was often very short, whereas the time to complete the landing process was much longer. In other words, the ankle joint was not dorsiflexed enough and did not have a complete buffer at peak vGRF, and the latter and the muscles could not properly absorb the force. Whole-body instability during landing may result in a shorter time to peak vGRF because, when the body was unstable, the center of gravity will change from one position to another.

When compared with the no-brace condition, the use of three ankle braces can all increase peak vGRF, but no significant difference existed ($P=0.237$). Wearing an elastic ankle brace and CPAB both increase peak vGRF by about 10%, while a semi-rigid ankle brace had no significant effect on peak vGRF ($t=0.106$, $P=0.564$). Figure 2 shows that the use of three ankle braces can all reduce T-PvGRF ($P<0.01$) and an elastic ankle brace and CPAB reduced T-PvGRF with 6-10 ms at the dropping height of 120 cm. Wearing ankle braces can also reduce MPM and MEM, according to the degree of MPM reduction, semi-rigid brace ($t=5.309$, $P<0.01$), CPAB ($t=3.816$, $P<0.01$) and elastic brace ($t=2.455$, $P<0.05$) were followed. Both CPAB and a semi-rigid ankle brace can significantly reduce MEM, and CPAB showed a more significant effect ($t=3.449$, $P<0.01$).

The assessment of kinematics parameters

Table 2 shows that the dropping heights had a significant effect on MDAD ($P<0.01$), MIAD ($P<0.01$), MDAV ($P<0.01$), and MIAV ($P<0.01$). When compared with the no-brace condition, wearing ankle braces can decrease MDAV and MIAV with no significant differences. According to the degree of MIAD reduction from large to small, CPAB was ($t=17.97$, $P<0.01$), semi-rigid brace was ($t=15.12$, $P<0.01$), and an elastic brace was ($t=4.201$, $P<0.01$). When compared with the elastic brace, CPAB, and the semi-rigid brace were more able to limit inversion, as they can each reduce MDAD by about 8° ($t=3.974$, $P<0.01$) and 15° ($t=8.264$, $P<0.01$).

Collectively, three ankle braces can restrict dorsiflexion and inversion during landings and maintain ankle joint stability on the coronal and sagittal planes, while CPAB provided greater inversion limitations than the other two ankle braces.

The assessment of energy parameters

Table 3 shows that increasing dropping heights significantly increased the work and maximum power ($P<0.01$). When compared with the no-brace condition and wearing an elastic brace, no significant differences existed in ankle work and maximum power ($P>0.05$), whereas the use of the semi-rigid brace or CPAB decreased the work ($t=3.331$, $P<0.01$; $t=5.107$, $P<0.01$) and maximum power ($t=6.711$, $P<0.01$; $t=7.237$, $P<0.01$). Therefore, subjects wearing CPAB can effectively reduce the amount of work and power, further allowing the ankle to absorb less energy.

The assessment of the subjective score

Table 4 shows the subjective scores of the subjects of the three ankle braces were all statistically significant ($P<0.01$), and the total scores from low to high were semi-rigid brace (19.20±2.99), elastic brace (21.91±3.25), and CPAB (23.37±3.08). 85% of the subjects agreed that CPAB restricted inversion and eversion more effectively than the elastic brace, and was more comfortable and soft than the semi-rigid ankle brace. Therefore, CPAB combined the advantages of the other two ankle braces, with good comfort, ease of use, high stability, and light constriction. All the subjects were satisfied with the appearance, function, and comfort of CPAB.

Discussion

Ankle injuries mainly occurred during parachute training and landing, and even led to irreversible injuries, which seriously affected army combat capability [11-13]. Therefore, paratrooper ankle protection is an urgent problem that needs to be solved. Luippold et al. developed an out-the-boot parachute ankle brace, which reduced ankle injury rates by 50% [14]. The U.S. Department of Defence Center for Health Promotion and Preventative Medicine suggested paratroopers should wear semi-rigid ankle braces in 2010 [15]. In Britain, Australia, Germany, and other developed countries, internal ankle support was widely used by paratroopers as necessary protective equipment [2, 8, 16]. Although air-filled ankle braces, EVC foam braces, and high-elastic-fiber ankle socks had been developed successively in China, no relevant report exists on whether or not they can effectively prevent ankle injuries [2, 3, 5, 17]. According to the epidemiological survey and preliminary biomechanical research conducted for this study, the injury mechanism was found to be excessive dorsiflexion and inversion of the ankle joint during HSPL, and it was also found that wearing ankle braces can effectively restrict ankle joint motion stability on the sagittal and coronal planes [2, 5]. Therefore, in this study, a built-in ankle brace suitable for Chinese paratroopers was designed and fabricated. Moreover, a large peak vGRF was the fundamental ankle injury cause in parachute landings [18]. The ideal novel parachute ankle brace can not only avoid excessive dorsiflexion and inversion during parachute landings but also effectively reduce the instantaneous GRF impact.

According to the anatomy of ankle joints, the strong deltoid ligament is on the medial, while the lateral calcaneofibular ligament, anterior talofibular ligament, and posterior talofibular ligament on the lateral are relatively weak [19]. Great GRF impacts easily caused the lateral collateral ligament injury and even ruptured during parachute landings. The novel military parachute ankle brace CPAB design should be complementary to the asymmetric anatomic ankle joint structure. Since the lateral ligaments are weak, greater strength materials should be used on the outside of CPAB to protect the ankle and vice versa. Collectively, in the CPAB, the rigidity and strength of the lateral malleolus side should be greater than that of the medial malleolus side.

CPAB design should also consider appearance, materials, and biomechanics. Several innovative points in CPAB are as follows: (1) High security. Hinged structure reinforcement was widely used in the medial and lateral malleoli of ankle braces, and the curved protection body conforming to the anatomical structure of the medial and lateral malleoli was rare [20, 21]. The hard aluminum strip was consistent with the anatomical contour of the lateral malleolus and effectively limited inversion. Moreover, the inside of the aluminum strip was covered with foam fabric to reduce friction between the lateral malleolus and CPAB, further protecting the skin there and avoiding severe stress from the aluminum support. (2) Heel protection. Preliminary biomechanical research showed that peak vGRF can reach more than 10 times that of BW [2]. The heel pad was utilized to prolong buffer time, reduce peak vGRF, scatter sole pressure, and change sole pressure distribution. (3) Great comfort level. CPAB raw material (pique fabric) reduced relative slip between the protection device and human skin and improved protection reliability. According to studies on textile moisture absorption [22], pique fabric was more air permeable, drier, and washable than knitted fabric. Van den Bekerom et al. used silicone membrane as the main ankle brace material, which was lightweight and breathable, whereas the surface was relatively smooth, with little friction and prone to slippage and displacement during strenuous exercises [23].

In this study, a gradable experimental jumping platform with heights of 40 cm, 80 cm, and 120 cm was utilized to obtain increasing landing speeds, since the actual height for Chinese parachuting ground training is less than 150 cm. In addition to kinetic and kinematic parameters, the advanced Anybody musculoskeletal model and reverse dynamics analysis could calculate 3D net torque, power, and work of the ankle joint. Many studies showed that vGRF increased significantly as the jumping height increased [10, 24-27], indicating that GRF suffered by subjects was positively correlated with the height. While T-PvGRF reflected landing buffering capacity in the early landing stage, this study showed that increasing the height significantly decreased T-PvGRF, which demonstrated body instability and center-of-mass deviation. However, the T-PvGRF increase did not mean that the landing was more stable; the study of simulated sideways roll parachute landing showed that the T-PvGRF value didn’t vary with the height [28]. Therefore, whether or not a correlation existed between T-PvGRF and jumping height remained to be verified by future experiments. Increasing height had a significant influence on the sagittal MPM, MDAD, MDAV, and coronal MEM, MIAD, and MIAV of the ankle joint, as well as the work and power. The ankle passively generated MPM and MEM to resist external torques (dorsiflexion moment and inversion moment) generated by GRF. Peak torque can be used as a sensitive indicator to evaluate muscle strength [29]. The ankle absorbed the energy and the plantar muscles applied the work to reduce the GRF impact and increase the buffer. Since greater angular velocity meant greater joint momentum, the ankle joint may absorb more energy and transfer energy along the lower limbs to the knee, hip, and spine [30].

In this experiment, the effect of wearing CPAB on the kinetic, kinematic, and energy parameters of the ankle joint was more significant than that of wearing an elastic ankle brace or a semi-rigid ankle brace. Thanks to the special lateral support structure, CPAB provided greater inversion limitation than the other two ankle braces. When compared with the wrapping elastic brace, the lace-up straps of the semi-rigid brace and the adhesive bands of CPAB more effectively limited dorsiflexion. Niu et al. investigated the effects of different ankle braces on lower limb biomechanics during HSPL and revealed that rigid ankle brace usage could enhance muscle activity [17]. Some scholars acknowledged that elastic deformation of the support structure on both sides of the ankle brace provided an eversion moment to overcome inversion and reduced the work [31]. Based on Janssen et al.’s [7] Constructs of Subjective Factors of Brace Use, the questionnaires were designed using the Likert 5 point scale for each evaluation index, including ease of use, quality, comfort, stability, hindrance, and satisfaction. In general, the CPAB score was considered superior to the other two braces. The comfort (3.00±0.33) and satisfaction (2.70±0.59) of the semi-rigid ankle brace were low due to the sharp edge and hard material. However, the low hindrance (2.90±0.18) and stability (3.10±0.42) scores of the elastic brace were attributed to the lack of rigid support structure and special protection for the medial and lateral malleoli. 85% of the subjects agreed that CPAB was more effective for ankle inversion and eversion restriction than the elastic brace, and more comfortable and soft than the semi-rigid brace. In the future, more paratroopers will be equipped with CPAB, and in turn, more subjective feedback will be acquired.

Conclusion

A novel military parachute ankle brace, CPAB, was designed and prepared according to the biomechanical characteristics of excessive dorsiflexion and inversion during paratroopers' HSPL. Biomechanical tests showed that increasing the dropping height resulted in greater peak vGRF and energy parameters, which may lead to ligament damage or even fractures during parachute landings. The CPAB more markedly restricted the motion of the ankle joint on the coronal and sagittal planes than the elastic and semi-rigid ankle braces. Therefore, the CPAB had the advantages of a novel appearance, high efficiency, and superior comfort, providing a reliable choice for parachute jumping and training in China.

Abbreviations

Chinese parachute ankle brace, CPAB; ground reaction force, GRF; vertical ground reaction force, vGRF; time to peak vGRF, T-PvGRF; half-squat parachute landing, HSPL; bodyweight, BW; maximal plantarflexion moment, MPM; maximal eversion moment, MEM; angular displacement of maximal dorsiflexion, MDAD; angular displacement of maximal inversion, MIAD; angular velocity of maximal dorsiflexion, MDAV; angular velocity of maximal inversion, MIAV.

Declarations

Ethics approval and consent to participate

The investigators obtained informed consent before enrolling participants in this study.

Consent for publication

Not applicable.

Availability of data and materials

The datasets during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

LY and HY were responsible for the study design; WD, LZY, WXD performed the research; YB and LLL analyzed the data; ZX and WD drafted the manuscript. All authors read and approved the final manuscript.

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Tables

Table 1. Kinetics parameters of ankle joint affected by three different dropping heights and ankle braces during half-squat parachute landig. (n=20)

Variables	Heights	No brace	Elastic brace	Semi-rigid brace	CPAB	P-value
Peak vGRF,	40cm	6.28±1.51	6.84±1.29	6.34±1.32	6.98±1.20	§
BW	80cm	7.25±1.92	7.91±1.71	7.44±2.13	7.91±1.35	P =0.237
	120cm	9.28±2.11	9.98±2.15	9.64±2.00	9.87±2.28	
Time to Peak vGRF (T-Peak vGRF), ms	40cm	54.47±6.03	45.16±4.76	50.55±6.16	47.55±5.59	§, a, c, d, f
	80cm	40.97±4.74	36.42±4.17	39.86±5.26	38.16±4.20	P < 0.01
	120cm	28.14±1.78	22.75±2.28	28.62±4.32	22.71±2.44	
Maximum plantar moment (MPM), Nm/kg	40cm	-3.10±0.86	-3.08±0.66	-2.20±0.89	-2.48±0.30	§, b, c, d
	80cm	-4.34±1.32	-4..33±0.83	-3.31±0.45	-3.74±0.43	P < 0.01
	120cm	-5.17±1.13	-4.43±1.25	-3.57±0.79	-4.02±1.60	
Maximum eversion moment (MEM), Nm/kg	40cm	-1.67±0.31	-1.50±0.44	-0.88±0.32	-0.66±0.21	§, b, c, d, e
	80cm	-1.97±0.47	-1.69±0.36	-0.94±0.45	-0.81±0.22	P < 0.01
	120cm	-2.15±0.50	-2.14±0.40	-1.73±0.28	-1.34±0.09	

§, significant differences among three dropping heights ($P < 0.05$); a, significant differences between the no-brace group and elastic brace group ($P < 0.05$); b, significant differences between the no-brace group and semi-rigid brace group ($P < 0.05$); c, significant differences between the no-brace group and CPAB group ($P < 0.05$); d, significant differences between the elastic brace group and semi-rigid brace group ($P < 0.05$); e, significant differences between the elastic brace group and CPAB group ($P < 0.05$); f, significant differences between the semi-rigid brace group and CPAB group ($P < 0.05$).

Table 2. Kinematics parameters of ankle joint affected by three different dropping heights and ankle braces during half-squat parachute landig. (n=20)

Variables	Heights	No brace	Elastic brace	Semi-rigid brace	CPAB	P-value
Angular displacement of maximal dorsiflexion (MDAD), °	40cm	18.97±3.76	18.12±3.28	15.22±4.01	16.94±2.15	§, b, c, d
	80cm	26.08±4.03	25.01±4.10	22.83±5.16	25.64±3.81	P < 0.01
	120cm	43.31±7.67	42.30±7.24	29.48±6.38	36.66±8.02	
Angular displacement of maximal inversion (MIAD), °	40cm	8.17±0.25	8.00±0.49	6.89±0.87	6.83±0.41	§, b, c, d, e
	80cm	13.19±0.93	13. 02±1.19	9.50±0.27	9.32±0.43	P < 0.01
	120cm	27.03±1.59	29.70±3.02	17.42±3.24	15.61±4.75	
Angular velocity of maximal dorsiflexion (MDAV), °/s	40cm	554.38±118.57	512.83±139.50	-2.20±0.89	469.24±70.39	§, b, c, d, e
	80cm	763.50±250.40	637.85±194.35	-3.31±0.45	620.37±125.20	P < 0.01
	120cm	1021.93±330.29	929.17±312.13	-3.57±0.79	859.77±330.93	
Angular velocity of maximal inversion (MIAV), °/s	40cm	339.83±21.39	297.92±18.17	249.99±22.57	286.03±20.31	§, b, c, d
	80cm	472.33±114.27	443.41±145.09	395.45±68.34	431.49±116.39	P=0.008
	120cm	588.42±195.45	564.72±216.36	500.16±264.36	533.97±129.04	

§, significant differences among three dropping heights (P < 0.05); a, significant differences between the no-brace group and elastic brace group (P < 0.05); b, significant differences between the no-brace group and semi-rigid brace group (P < 0.05); c, significant differences between the no-brace group and CPAB group (P < 0.05); d, significant differences between the elastic brace group and semi-rigid brace group (P < 0.05); e, significant differences between the elastic brace group and CPAB group (P < 0.05); f, significant differences between the semi-rigid brace group and CPAB group (P < 0.05).

Table 3. Energy parameters of ankle joint affected by three different dropping heights and ankle braces during half-squat parachute landig. (n=20)

Variables	Heights	No brace	Elastic brace	Semi-rigid brace	CPAB	P-value
Peak power, W	40cm	-8.49±1.33	-8.14±0.76	-6.42±0.25	-5.80±0.23	§, b, c, d, e
	80cm	-21.34±8.06	-19.25±6.88	-17.57±8.14	-17.60±8.50	P < 0.01
	120cm	-44.03±16.72	-41.82±13.21	-26.17±9.52	-24.77±7.21	
Work, J/kg	40cm	-0.75±0.13	-0.78±0.10	-0.45±0.09	-0.29±0.06	§, b, c, d, e
	80cm	-1.28±0.34	-1.27±0.35	-1.10±0.30	-1.08±0.34	P < 0.01
	120cm	-1.70±0.37	-1.68±0.42	-1.59±0.36	-1.43±0.22	

§, significant differences among three dropping heights (P < 0.05); a, significant differences between the no-brace group and elastic brace group (P < 0.05); b, significant differences between the no-brace group and semi-rigid brace group (P < 0.05); c, significant differences between the no-brace group and CPAB group (P < 0.05); d, significant differences between the elastic brace group and semi-rigid brace group (P < 0.05); e, significant differences between the elastic brace group and CPAB group (P < 0.05); f, significant differences between the semi-rigid brace group and CPAB group (P < 0.05).

Table 4. The score results of three kinds of ankle braces.

Variables	Elastic brace	Semi-rigid brace	CPAB	F	P-value
Ease of use	3.70±0.38	3.90±0.12	4.10±0.27	10.36	P < 0.01, b
Quality	3.60±0.40	4.10±0.28	3.80±0.12	15.03	P < 0.01, a, c
Comfort	4.00±0.15	3.00±0.33	3.70±0.26	79.40	P < 0.01, a, b, c
Stability	3.10±0.42	4.00±0.22	3.60±0.23	43.93	P < 0.01, a, b, c
Hindrance	2.90±0.18	3.70±0.36	3.50±0.32	39.33	P < 0.01, a, b
Satisfaction	3.30±0.43	2.70±0.59	4.40±0.26	74.26	P < 0.01, a, b, c
total scores	21.91±3.25	19.20±2.99	23.37±3.08	9.267	P < 0.01, a, c

a, significant differences between the elastic brace group and semi-rigid brace group (P < 0.05); b, significant differences between the elastic brace group and CPAB group (P < 0.05); c, significant differences between the semi-rigid brace group and CPAB group (P < 0.05).

Figures

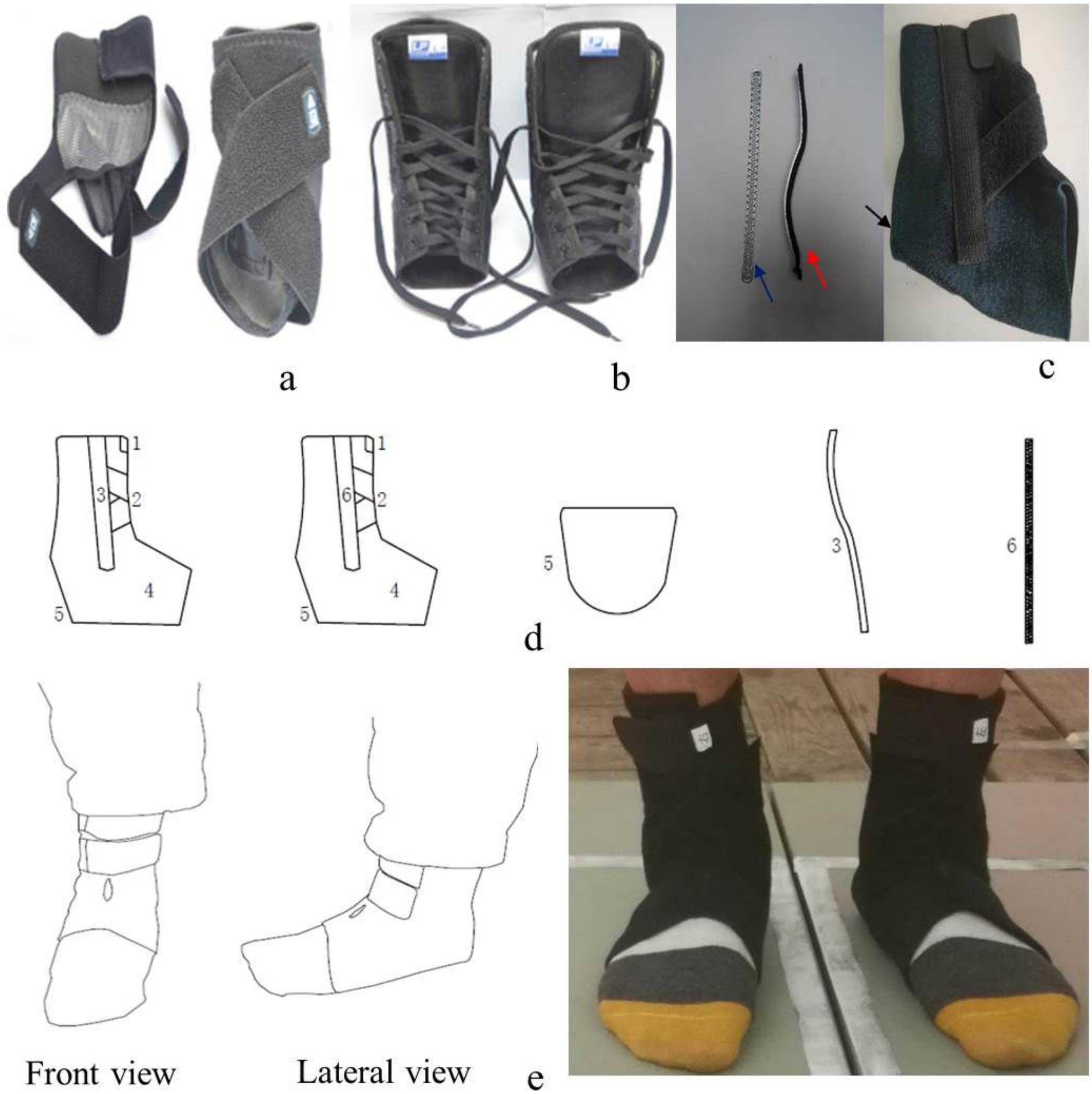

Figure 1

Three types of ankle braces used in the experiment: (a) The elastic ankle brace (AQ5261EA, Tokyo, Japan) (b) The semirigid ankle brace (LP787, Seattle, WA, USA) (c) CPAB. Elastic metal spring strip (blue arrow); an aluminum strip embedded with foam fabric that fits the lateral malleolus profile (red arrow); Heel pad (black arrow). (d) Schematic structure diagram. 1, 2 adhesive bands; 3, aluminum strip; 4, the body of CPAB; 5, heel pad; 6, elastic metal spring strip (e) overview of CPAB.

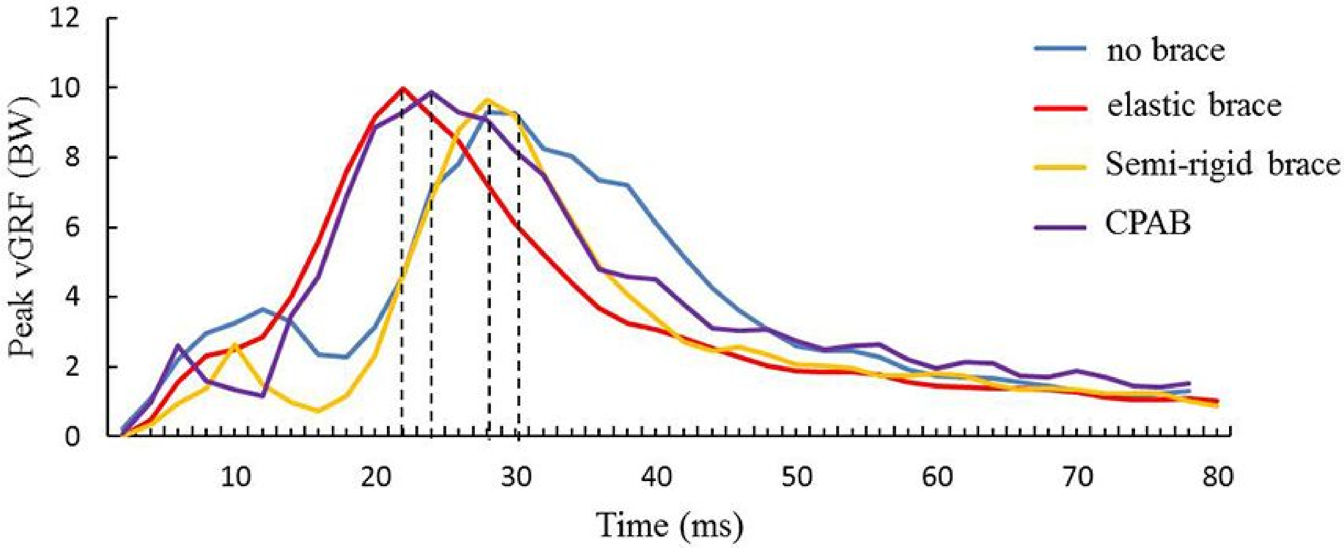

Figure 2

Time-dependent curves of vGRF during half-squat parachute landing under different ankle braces conditions at 120cm.