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地表面倾斜度与踝关节护具对垂直着地运动中地面反作用力、踝关节运动学和动力学的效应

Songning Zhang(美)[1],Qingjian Chen(美)[2],Michael Wortley(美)[1],Divia Bhaskaran(美)[3]

摘　要: 现有研究文献尚无有关在着地过程中不同表面倾斜度和踝关节护具效应的运动学、动力学和地面反作用力的综合数据。通过对比25° 斜面和平面的着地以及使用和不使用踝关节护具情况下来检测踝关节的生物力学特性。研究方法：11名健康受试者 [年龄：(24.6±3.5)岁,身高:(24.6±0.10) m,质量:(65.6±14.9) kg]参与本次研究。受试者在4个动态运动条件下各进行5次实验：从0.45 m高处垂直下落至25° 的斜面（IS）或平面(FS)上,使用或不使用半刚性踝关节护具,同时采集三维运动学和测力台地面反作用力数据。利用2×2(表面X踝关节护具)的重复测量方差分析来评估选定的变量。研究结果:与平面着地相比,斜面着地造成较小的垂直和内侧地面反作用力峰值。研究还发现踝关节背曲运动范围、着地角度和背曲速度、最大外翻与跖曲角速度提高,但产生了更大内翻角度和运动范围、着地内翻速度和最大跖曲力矩。踝关节护具在斜面着地时减少了达到地面反作用力第二垂直峰值的时间、着地角度、背曲速度、最大外翻和跖曲速度,但增加了跖曲力矩的最大值。研究结论:斜面增加踝关节额状面的运动范围和踝关节负荷。但是,就斜面着地而言,踝关节护具对踝关节额状面的运动范围和踝关节负荷的影响是相当有限的。

关键词: 踝关节扭伤;着地;斜面;踝关节护具;生物力学

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Effects of inverted surface and ankle brace on ground reaction force and ankle kinematics and kinetics during landing

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Abstract: Background: Currently there are no comprehensive data in the literature on effects of different surface inclination and ankle brace on ankle kinematics, kinetics and GRF in landing activity. The purpose of the study was to examine ankle biomechanical characteristics during drop landing on a 25° inverted surface with an ankle brace compared to landing on a flat surface, both with and without an ankle brace. Method: A total of 11 healthy subjects (age: 24.6 ± 3.5 years, height: 1.70 ± 0.10 m, mass: 65.6± 14.9 kg) participated in this study. Subjects performed five trials in each of four dynamic movement conditions: drop landing

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from 0.45 m onto a 25° inverted surface and flat surface with and without a semi-rigid ankle brace. The three-dimensional kinematics and ground reaction forces (GRF) were collected simultaneously. A 2 × 2 (surface × brace) repeated measures analysis of variance was used to evaluate selected variables. Results: Landing on the inverted surface caused smaller peak vertical and medial GRFs but greater lateral GRF compared to landing on flat surface It also introduced reduced dorsiflexion range of motion (ROM), contact and maximum dorsiflexion velocities and plantar flexion moment, but greater inversion angle and ROM, contact inversion velocity and peak eversion moment. The ankle brace decreased the time of 2nd peak vertical GRF, contact angle and dorsiflexion velocity, and maximum eversion velocity and plantarflexion velocity, but increased maximum plantarflexion moment in inverted surface landing. Conclusions. These results suggest that the inverted surface increased frontal-plane ROM and loading of ankle complex. In addition, the effects of the ankle brace on frontal-plane ROM and loading of ankle complex is rather limited during landing on the inverted surface.

Key Words: ankle sprain; landing; inverted surface; ankle brace; biomechanics

0 引 言

踝关节是人体在运动中最容易受伤的部位之一，在运动相关损伤中高达 10%~30 %。在踝关节损伤中，踝关节外侧韧带扭伤是最常见的[1,2]。关于侧踝关节损伤和踝关节护具效果的研究普遍地借助脚踝翻转下落平台[3-10]。然而，翻转下落试验从静止位置开始，且下落高度受装置高度(20 cm 左右[11]所限。事实上，许多侧踝关节损伤发生的降落高度高于上述测试方式[12-14]。

之前关于翻转降落和斜面着地的对比表明，斜面着地的要求更高，因为它表现出更早的踝关节内翻动作和更快的内翻速度[11]。因此，对于研究踝关节护具而言，斜面着地实验应该是一个更实际、更适合的方案。关于在斜面下降着地的研究在生物力学和运动医学的文献中非常有限。它只被用在一个检测踝关节护具影响的研究中 [15]。Venesky发现，相比而言，使用踝关节护具会产生更大的踝关节外翻力矩、膝关节外旋扭矩[15]。研究使用了一个 20° 的倒面，这个角度比大多数翻转下降装置常用的 30° 翻转角度小。但该研究缺乏有关地面反作用力(GRF)的数据。Hodgson 等人[16]发现最大垂直地面反作用力和脚趾接触负荷度明显增加，而踝关节在平整表面着地下时，相比没有踝关节护具而言，使用踝关节护具时脚趾接触的脚踝角度显著下降。

虽然踝关节护具在含有跳跃着地的运动项目中经常使用，但现有文献却很少关注他们在着地过程中的效用。McCaw 等人[17]研究了使用踝关节护具时的软、硬着地方式，并发现使用踝关节护具可显著降低最大踝关节矢状面角速度。相反，Ubell 等人测试了使用两个半刚性踝关节护具和一个绑带式踝关节护具加一足跖面支点跳跃着地成功率[18]。半刚性踝关节护具下进行在鞋底附着一个 24° 内翻支点，从一英尺高度着落在一个平面，保持 3 s 平衡的试验中显示出更高的成功率[11]。

目前尚无不同倾斜角度对踝关节护具和无护具条件下着地运动的踝关节动力学和地面反作用力影响的综合数据。这些数据可以提供与侧踝关节扭伤有关的相关信息。因此，本研究的目的在于探讨着地过程中，斜面和半刚性踝关节护具对踝关节的运动学和地面反作用力的影

INTRODUCTION

The ankle is one of the most traumatized body sites in sports and accounts for 10-30% of all sports related injuries[1]. Of those ankle injuries, sprains of the lateral ankle ligaments is most common[1,2]. Research investigating lateral ankle sprain and effects of ankle braces has typically utilized a rapidly induced inversion drop using an ankle inversion drop platform (trap door)[3-10]. However, the inversion drop test starts the inversion drop from a static position and drop height is limited by the height of the device, which is about 20 cm[11]. Many lateral ankle sprains occur while landing from a jump[12-14] in which the landing height is usually higher than the drop height allowed by an inversion drop platform.

Previous comparisons between inversion drop and inverted surface landing indicated that the inverted surface landing is more demanding as it introduces earlier ankle inversion and greater inversion velocity[11]. Therefore, drop landing on an inversion surface should be a more realistic and suitable protocol for investigating the effect of ankle bracing compared to the inversion drop. Research on drop landing on an inversion surface is very limited in biomechanics and sports medicine literature. It has only been used in one study examining the effects of an ankle brace[15]. Venesky found a greater ankle eversion torque, and knee external rotation torque wearing an ankle brace during drop landing compared to wearing no brace[15]. An inverted surface of 20° was used in the study and this angle is slightly smaller than the common inversion angle of 30° used in most inversion drop device studies. No ground reaction force (GRF) or kinematic data were available in this paper. Hodgson et al.[16] found that the peak vertical GRF and loading rate at toe contact significantly increased while the ankle angle at toe contact significantly decreased during drop landing on flat surface wearing an ankle brace compared to no brace.

Although ankle brace is commonly used in sports that involve jump and landing, their effectiveness during landing activities has received relatively limited attention in literature.

响。本研究的假设是,相比平面着地,斜面着地将产生更大的内侧向GRF峰值、踝关节内翻角和角速度峰值、外翻力矩峰值,以及较小的垂直GRF峰值。然而,使用踝关节护具将减少两个测试方案之间的这些变量的差异。

1 研究方法

本实验共有11名健康且积极的受试者[年龄:(24.6±3.5)岁,身高:(1.70±0.10) m,质量:(65.6±14.9) kg],其中包括6名女性和5名男性,该实验对象招募自一所大学及其周边社区。受试者无任何重大下肢损伤,实验前6个月内无侧踝关节损伤,且在测试之前无各类踝关节损伤史。受试者在测试前均签署了审查委员会批准的知情同意书。

受试者在测试开始时被要求填写关于她/他的伤病史、体力活动、人口信息的问卷。该测试在热身之后开始。热身包括在跑步机上进行速度为3.4英里/小时的4 min跑和大肌肉群拉伸(包括肩、躯干、髋关节、膝关节和踝关节)。然后受试者在4种0.45 m高处下降着地运动条件下各进行了5次试验:(1)使用踝关节护具条件下的斜面(IS)着地;(2)使用半刚性踝关节护具(Element,DeRoyal工业有限责任公司,使用说明)条件下的斜面着地;(3)不使用踝关节护具条件下平面(FS)着地;(4)使用半刚性踝关节护具条件下平面着地。被测者在无踝关节护具和有踝关节护具条件下穿着一双跑鞋(Noveto,阿迪达斯)。25° 斜面[45.72 cm(L)× 22.86 cm(W)× 11.43 cm(H),图1)被安装在右侧测力平台的顶部,平面[40 cm(L)× 40 cm(W)× 4 cm(H)]安装在左侧测力平台的顶部,在(1)和(2)中,砂纸带被粘附在表面来确保着地不打滑。25° 斜面的确定是经过广泛的预测试后确立的,能够实现最大化的踝关节内翻而不造成实际的踝关节扭伤[11]。平面高度(4 cm)低于斜面中点高度(5.72 cm),以确保参与者右脚先接触斜面。踝关节护具配备了脚跟骨系带系统,且已被证明能有效控制斜置下降和横向切割运动中踝关节的内翻运动[19]。

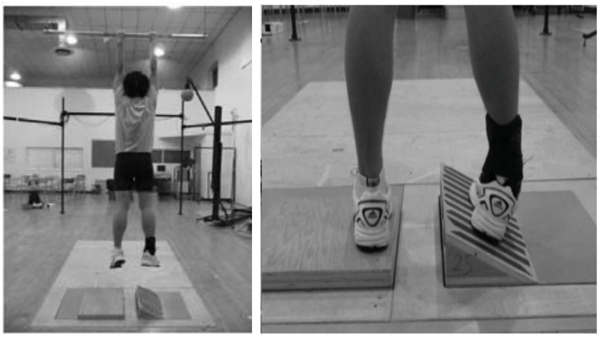


图1 在斜面上垂直脱手着地

Figure 1 Drop landing onto inverted surface

一个由7部红外摄像机组成的运动分析系统(240 Hz,Vicon Motion Analysis Inc.,牛津,英国)被用于收集运动测试中的三维(3D)运动学数据。解剖标记反光球放置于两侧髂嵴,股骨大转子,外侧和内侧髁,内外侧踝,以及第一和第五跖骨的头部[20]。附着在热塑性壳的4个跟踪反光球群通过一弹性膜被放绑置在骨盆、大腿和小腿的侧中间部,3个跟踪反光球直接放置在鞋的后外侧鞋跟,踝关节的

McCaw and colleagues[17] examined soft and stiff landing styles using drop landing wearing ankle braces and found a significantly reduced maximum ankle sagittal-lane angular velocity while wearing an ankle brace. Conversely, Ubell and colleagues tested the success rates of a specific jump landing task wearing two semi-rigid braces and one lace-up brace with a fulcrum affixed to the plantar surface of the landing foot [18] . The semi-rigid braces showed significantly greater success rates in keeping balance for three seconds after a one-foot landing onto a flat surface with a 24° inversion fulcrum affixed to the heel of the shoes compared to the lace-up brace and no brace conditions[11].

Currently there are no comprehensive data in the literature on the effect of different surface inclination on ankle kinetics and GRF in landing activity in braced and unbraced conditions. Such information can provide loading related information associated with lateral ankle sprains. Therefore, the purpose of the study was to investigate effects of an inverted surface and a semi-rigid ankle brace on ankle kinematics and kinetics, and GRF during drop landing. It was hypothesized that landing on the inverted surface would introduce greater peak mediolateral GRF, peak ankle inversion angle, peak inversion velocity, and peak eversion moment but smaller peak vertical GRF compared to the flat surface landing. However, wearing an ankle brace would reduce the differences in these variables between the two testing protocols.

METHODS

A total of 11 healthy and physically active participants (age: 24.6±3.5 years, height: 1.70±0.10 m, mass: 65.6±14.9 kg), 6 females and 5 males, were recruited to participate in this study from a large university and its surrounding community. The participants were free from any major lower extremity injury, free from lateral ankle sprains within 6 months, and with no history of multiple ankle sprains prior to the testing. Participants signed the informed consent form approved by the Institutional Review Board prior to testing.

The participant was asked to fill out questionnaires about his/her injury history, physical activity, and demographic information at the beginning of the test session. It was followed by a warm-up of running on a treadmill at 3.4 miles/hour for 4 minutes and stretching of major muscle groups including shoulder, trunk, hip, knee, and ankle joints. The participant then performed five trials in each of four drop landing movement conditions from 0.45 m on to: 1) an inverted surface without an ankle brace, 2) an inverted surface with a semi-rigid ankle brace (Element, DeRoyal Industries, Inc, TN), 3) a flat surface without ankle brace, and 4) a flat surface with the ankle brace. The subject wore a pair of lab running shoes (Noveto, adidas) in no brace and braced conditions. The 25° inverted surface [45.72 cm (L) ×22.86 cm (W)×

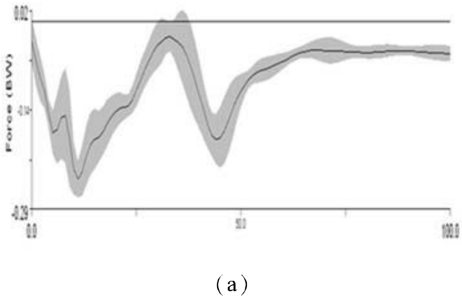
解剖标记反光球被分别放置在估计的踝关节护具外相应的内外踝的位置。两台 3D 测力台(1 200 Hz,AMTI,水城,MA,USA)被用来同时测量地面反作用力(GRF)和其力矩。3D 运动学和 GRF 的数据均由 VICON 工作站软件收集。受试者亲身实践并熟悉足踝护具,做落地运动,直到他/她感到适应为止。护具条件(有或没有踝关节护具)的测试顺序首先随机生成。地表条件(落地在斜面和平面)的测试顺序在每个护具条件下再随机生成。收集两次独立的静态标定测试,一次是两个平面和斜置表面落地条件下没有使用踝关节护具,另一次是使用踝关节护具下的平面和斜面落地条件。所有下降落地试验是由被试者从一个高度可调的"单杠"上开始,从降落高度定为 0.45 m(从中脚跟到测力平台或斜面中间测量)分别执行。在斜面落地测试中,要求被试者正常落地,左脚降落在左测力台上,而右脚降落在斜面的中间。并要求被试者落地时目视前方。一个成功的测试中,受试者落地时各个方向都未失去平衡。

对三维(3D)标记的位置和 GRF 数据用一个 4 阶 Butterworth 低通滤波器,各自通过 8 Hz 和 50 Hz 的截止频率来平滑。下降落地运动是从脚接触到最大膝关节屈曲时段进行分析。三维运动学和动力学变量使用 Visual3D(C-Motion,日耳曼,MD,USA)计算并使用 XYZ 旋转序列。关节角度运动学和力矩的约定用右手法则确定。关节力矩被计算为内力矩。关键点(最大、最小值)是由自编的计算机程序(VB_V3D,MS VisualBasic6.0)用 Visual3D 的输出确定。本研究仅使用右侧下肢的数据进行分析。重要的变量包括峰值垂直和内侧 GRF,接触时额状面踝关节角度和速度,最大内旋角度/外翻角度和速度,内翻/外翻 ROM,接触和最大跖曲角度和速度,最大背曲角度和速度,以及 GRF 和运动学变量有关的时间参数。GRF 数据标准化为体重(BW),关节力矩标准化为体质(N·m/kg)。一些有关斜面落地条件的数据已经在别处报告[11],用于和平面的落地进行比较。

护具和落地表面的效应均通过 2× 2(地表× 护具)重复测量的方差(ANOVA)分析,显著水平设为 0.05(15.0,SPSS,SPSS 公司,芝加哥,IL)。当发现地面和护具条件之间存在显著的交互作用,使用 t 检验检测地表状态和护具条件之间的差异。

2 研究结果

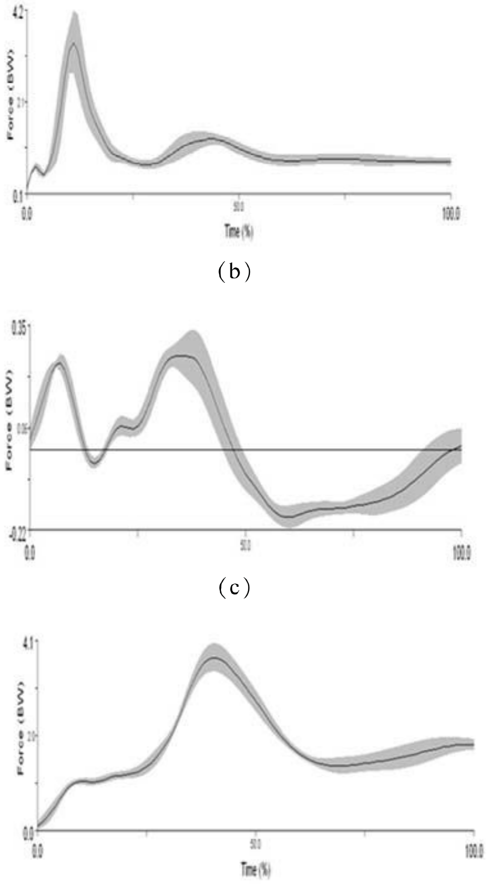
图 2a-d 中显示的是两种表面条件下的水平和垂直 GRF 曲线。统计结果表明:FS 着地的垂直 GRF 峰值比 IS 着地显著提高 ($p=0.004$, 表 1)。而且, 斜面着地的 peak mediolateral GRF 显著地下降($p=0.018$,表 1)。



(a)

11.43 cm (H), Figure 1) was mounted on the top of a force platform on right side while the flat surface [40 cm (L) × 40 cm (W) × 4 cm (H)] was mounted on the top of a force platform on the left side, in the conditions 1 and 2. Strips of sand paper were adhered to the inverted surface to ensure proper landing without slipping. The 25° inversion slope was determined after extensive piloting testing to maximize ankle inversion without causing an actual lateral sprain [11]. The height of the flat surface (4 cm) was determined so that it was lower than the mid height of the inverted surface (5.72 cm), to ensure that the participant contacted the inverted surface with the right foot first. The ankle brace was equipped with a heel strapping system and has been shown to be effective in controlling inversion motions in inversion drop and lateral cutting[19].

A 7-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain the three-dimensional (3D) kinematics during data collection. Reflective anatomical markers were placed bilaterally on the iliac crest, greater trochanter, lateral and medial epicondyles, lateral and medial malleoli, and the head of first and fifth metatarsal [20]. A cluster of four tracking markers affixed to a thermoplastic shell was placed on the mid portion of the pelvis, thighs, and shanks via a neoprene elastic wrap. Three tracking markers were placed directly to the posterior and lateral heel counter of the shoes. The anatomical markers for the ankle joint were placed at estimated ankle malleolus positions outside of the ankle brace. Two force platforms (1200 Hz, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the ground reaction forces (GRF) and the moments of forces simultaneously. 3D kinematic and GRF data were collected simultaneously by the Vicon workstation software. The participant was given practice landing trials to become familiar with the ankle brace, landing movement, and inverted surface prior to the actual testing until he/she felt comfortable. The order of brace conditions (with or without brace) was first randomized. The testing surface conditions (drop landing on inverted surface and flat surface) were then randomized for each brace condition. Two separate static calibration trials were collected, one without ankle brace for the two flat and inverted surface landing conditions, and one with ankle brace for the flat and inverted surface landing conditions. All drop landing trials were performed from an over-head bar controlled by an electrical hoist from a landing height set at 0.45 m measured from the mid-heel to the force platform or the middle of the inverted surface for flat and inverted surface landing conditions, respectively. In the landing on to the inverted surface, the subject was asked to land normally; the left foot landed on the left force platform while the right foot landed on the middle of the inverted surface. To be consistent, the subject was asked to look for wards during



(b)

(c)

(d)

注：平面着地中的(a)内外侧水平 GRF，(b)垂直 GRF，斜面着地中的(c) 内外侧水平 GRF，(d) 垂直 GRF。

图 2 某被试者的平均数据图

Figure 2 Representative ensemble curves

表 1 平均地面反用力（GRF）峰值，额状面脚踝运动学和动力学变量（均值±标准差）

Table Ⅰ Average peak ground reaction force, frontal plane ankle kinematic and kinetic variables: mean±SD

变量	平面		斜面	
	无护具	有护具	无护具	有护具
垂直 GRF 峰值（体重）[a]	3.20±0.64	3.38±0.73	2.86±0.55	2.69±0.56
内侧 GRF 峰值 (体重)[a]	-0.31±0.08	-0.28±0.08	-0.21±0.07	-0.23±0.11
内翻着地角 (°)[a b]	5.6±3.4	2.2±2.3	11.8±3.2	8.4±3.2
最大内翻角 (°)[a]	5.3±3.9	1.8±4.8	25.3±3.9	22.5±5.2
最大外翻力矩 (Nm/kg)[a]	-0.33±0.16	-0.22±0.17	-0.94±0.19	-0.90±0.15

注：a：由于地表面不同而产生显著影响；b：由于有无护具而产生显著影响。

额状面运动学结果证实，与 IS 相比，FS 存在一个显著降低的着地内翻角（p=0.001）；相对于无踝关节护具，带有踝关节护具亦是如此（p=0.015，表 1）。FS 着地表现出了外翻运动而 IS 着地表现出了相反的内翻运动（图 3）。相对 FS 着地，IS 着地中最大内翻角有显著增加（p=0.001）。

landing. A successful trial was a trial where the subject landed without losing balance in any direction.

Three-dimensional (3D) marker position data and GRF data were smoothed using a 4th order Butterworth low-pass filter with cutoff frequencies of 8 and 50 Hz, respectively. The drop landing movement was analyzed from foot contact to maximum knee flexion. Three-dimensional kinematic, GRF, and joint moment variables were computed in Visual3D (C-Motion, Inc., Germantown, MD, USA) using an X-Y-Z Cardan rotational sequence. The conventions of the joint angular kinematics and moments were determined using the right-hand rule. The joint moments were computed as internal moments. Critical events were determined using a customized computer program (VB_V3D, MS VisualBasic 6.0) from the output of Visual3D. Only the data from the right limb was analyzed. The variables of interest included peak vertical and mediolateral GRF, contact frontal plane ankle angle & velocity, maximum inversion angle/eversion angle & velocity, inversion/eversion ROM, contact plantarflexion angle, maximum dorsiflexion angle & velocity, times to peak GRFs and kinematic variables. The GRF data were normalized to body weight (BW) and joint moments were normalized to body mass (Nm/kg). Some of the data for the inverted surface (IS) landing conditions have already been reported elsewhere [11] and are used for comparisons with flat surface (FS) landing.

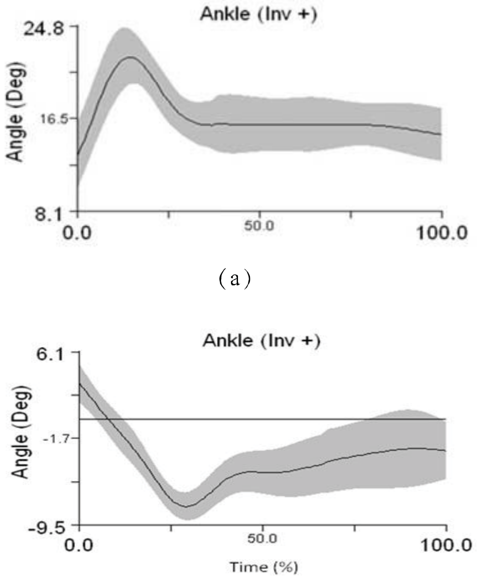
Effects of both brace and surface during landing were examined using a 2 × 2 (surface × brace) repeated measures analysis of variance (ANOVA) with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL). A paired t-test was used in post hoc comparisons to detect the differences between the surface conditions and brace conditions when a significant surface and brace interaction was found.

RESULTS

Representative curves of the horizontal and vertical GRF curves for both surface conditions are provided in Figure 2a – d. The statistical results of the landing activities showed a significantly higher peak vertical GRF (p = 0.004) in FS landing compared to IS landing (Table 1). Furthermore, the inverted surface caused a significant decrease in the peak mediolateral GRF (p = 0.018, Table 1).

The results of the frontal plane kinematics showed a significantly decreased inversion angle at contact in FS compared to IS (p = 0.001) and with ankle brace compared to the no brace conditions (p = 0.015, Table 1). The FS landing showed an eversion motion while IS landing showed an inversion motion (Figure 3). The maximum inversion was increased in IS landing compared to FS landing (p = 0.001). The ankle brace caused a reduction in maximum inversion angle but the effect was not significant (p = 0.053). The peak eversion moment was increased in IS landing compared to FS

踝关节护具导致最大内翻角下降，但是结果不显著(p=0.053)。相对于 FS，IS 着地中最大内翻力矩提高了(p=0.001，表 1)。



(a)

(b)

注：(a) 斜面着地，(b) 平面着地。

图 3 被试者的踝关节角度平均数据图

Figure 3 Representative ensemble frontal plane ankle angle curves during

矢状面运动学表明在使用踝关节护具的条件下，踝关节着地角度（p=0.001）和背曲 ROM 有着显著性地下降(p=0.001，表 2)。相比 IS 着地，FS 着地有着更大的背曲 ROM（p = 0.001)。与 FS 相比，IS 的背曲速度峰值下降(p = 0.001）。与不使用踝关节护具相比，使用踝关节护具的条件下背曲速度峰值(p = 0.001)同样下降。另外，与 FS 着地相比，IS 着地的踝关节最大跖曲力矩下降 (p = 0.045)；该指标在使用踝关节护具比不使用踝关节护具同样下降(p=0.012)。

表 2 平均矢状面运动学和动力学变量(均值±标准差)

Table Ⅱ Average sagittal plane kinematic and kinetic variables: mean ± SD

变量	平面		斜面	
	无护具	有护具	无护具	有护具
跖曲着地角(°)^{b}	-18.5±8.7	-7.1±6.0	-17.9±9.2	-5.0±8.7
背曲运动幅度(°)$^{a\,b}$	44.4±7.9	35.2±5.1	35.3±5.1	28.1±6.2
最大背曲速度(°/s)^{ab}	788.4±138.1	643.7±108.9	662.2±140.5	504.5±144.4
跖曲力矩 (Nm/kg)$^{a\,b}$	-1.27±0.52	-1.65±0.41	-1.17±0.23	-1.39±0.28

注：a：由于地表面不同而产生显著影响；b：由于有无护具而产生显著影响。

3 讨论

本研究的主要假设是 IS 着地导致最大内侧 GRF、内翻角和外翻力矩的增加，但造成最大垂直 GRF 减低。本研

landing (p = 0.001, Table 1).

Results of the sagittal plane kinematics showed that the contact angle (p = 0.001) and dorsiflexion ROM (p = 0.001) were significantly reduced while wearing the ankle brace (Table 2). FS landing had significantly greater dorsiflexion ROM compared to IS landing (p = 0.001). The peak dorsiflexion velocity (p = 0.001) were reduced in IS landings compared to FS landings. The peak dorsiflexion velocity (p = 0.001) were also decreased with ankle brace compared to no brace landing conditions (Table 2). In addition, the peak ankle plantarflexion moment was increased in IS landing compared to FS landing (p = 0.045) and reduced in the braced landing conditions compared to unbraced conditions (p = 0.012, Table 2).

DISCUSSION

The primary hypothesis was that landing on the inverted surface would cause greater peak mediolateral GRF, peak inversion angle and eversion moment but smaller peak vertical GRF compared to the flat surface landing. The hypothesis was partially supported by the results of this study. In the inverted surface landing, we observed smaller second peak vertical GRFs compared to FS landing. We initially thought that the higher 1st peak vertical GRF in the FS landing may be due to a toe-heel landing strategy used. A closer examination of sagittal kinematic results showed that subjects exhibited similar contact plantarflexion angles in both surface landing conditions. This was coupled with smaller dorsiflexion ROM in IS compared to FS landing (Table 3), suggesting a stiffer landing style adopted on the inverted surface. It has been suggested that during normal drop landing (onto flat surface) the body cannot maximize the energy absorption capacity of ankle plantarflexors compared to stiff landing [21]. In IS landing, the inverted surface not only forces ankle joint to be in an inverted position at contact but a more plantarflexed position throughout the landing phase, resulting in the reduced dorsiflexion ROM. More importantly, the inverted surface may redirect the GRF vector to a more lateral direction and therefore reduce vertical component. This reduced vertical GRF may also explain the decreased peak dorsiflexion velocity and peak plantarflexion moment. The amount of energy absorption is normally related to the amount of ROM in the lower extremity joints [22-24].

The stiff landing strategy associated with the inverted surface, which is reflected in the reduced dorsiflexion ROM, may also indicate a need to co-contract ankle joint muscles to stabilize the ankle joint and avoid injury in the unstable IS landing condition. Although the sagittal plane ankle kinematics is significantly changed in IS landing, the frontal plane ankle kinematics was modified even more. The inverted surface eliminates eversion motion that is observed in the normal FS

究的结果只是部分地支持该假设。IS着地与FS着地相比，最大垂直GRF(第二峰值)减低。而第一垂直GRF峰值(与前脚掌着地有关)升高，我们起初认为这是由于FS脚尖—脚跟着地方式引起的。进一步数据分析表明在两种不同地面上着地方中，被试者的着地跖曲角都相似。同时IS着地显示出较小的背曲的运动幅度，表明IS着地方式更硬性。有研究表明，与硬性着地相比，正常平面着地情况下人体的跖曲肌群不能更好地吸收能量[21]。IS着地过程中，斜面不仅导致踝关节内翻，还使其在整个着地过程中处于更趾曲的位置，从而导致踝关节背曲运动幅度下降。更重要的是，斜面使GRF方向转变成更水平的方向，从而导致垂直GRF降低。垂直GRF的减少也与背曲角速度和跖曲力矩峰值下降有直接关系。而着地中能量的吸收与下肢关节的运动幅度有直接关系[22-24].

在斜面上着地方式是硬性的，其被反映在降低的背曲ROM中，这也说明踝关节主抗肌肉共收缩来保持踝关节的稳定性，以避免在不稳定的IS着地条件下受伤。尽管矢状面运动学数据在IS着地时发生了显著的变化，但是额状面踝关节运动学数据变化得更多。斜面除去了在正常FS着地中的外翻运动。侧踝关节韧带和踝关节外转肌在IS着地中对抵抗踝部内翻起着非常重要的作用，在IS着地条件下踝关节外翻力矩增加可以证明这一结论。增加的外翻力矩进一步揭示了外侧踝韧带和关节结构上的负荷也增加了。相对平整表面而言，在IS着地条件中减少的峰值垂向GRF和侧向GRF部分是由于脚接触面不是非常垂直于斜面并且摩擦有所增加。

在IS着地中减少的水平GRF峰值无法证明我们开始的假设。对GRF曲线进一步研究表明，尽管内侧GRF峰值在IS着地时减少，但是外侧GRF实际上却增加了(图2a和c)，这与在斜面上踝关节内翻角运动和速度的增加相吻合。与FS着地相比，IS着地接触内翻角和峰值反向角分别多出了6°和20°。此外，在IS着地触地时踝关节具有内翻斜速度，而FS着地触地时踝关节具有外翻速度。为了避免IS着地中发生滑动，我们在斜面上安装了砂纸条。在着地阶段增加的摩擦可以使脚固定在斜面上并且向下的动量可以使踝关节处于极端的内翻位置。在IS着地中，GRF矢量可以远离内翻轴，产生更大的外部内翻力矩，这需要更大的内部外翻肌力矩对抗。为了避免在翻转时保持脚踝位置平衡对外侧韧带产生伤害，在IS着地时，踝关节肌肉表现出较大的外翻力矩。此外，在触地时增加的内翻角使踝关节外侧韧带和踝关节肌肉处于拉紧的状态，以便让韧带和肌肉在限制内翻和衰减冲击力方面做出更大的贡献。本次研究结果表明，IS着地试验方式对于研究踝关节损伤机制更合适，但难度更高，相对在平地上着地，IS着地在脚踝上增加了更多的内翻负荷。很多脚踝外侧扭伤都是发生在跳跃着地到一个不平的表面上，这使脚踝处于一级内翻位置[16]。

我们的第二个假设是使用踝关节护具将减少两个不同的测试方式中的GRF和运动学、动力学变量的差异。使用踝关节护具在着地时没有显著改变垂直和水平GRFS的峰值支持了这一假说。然而，Hodgson等人[16]发现在平

landing. The lateral ankle ligaments and ankle evertor muscles play a major role in resisting the inversion during IS landing. This is supported by the increased peak eversion moment in IS landing conditions in our results. The increased eversion moment further indicates increased mechanical loading to the lateral ankle ligaments and joint structures. The reduced peak vertical GRF and mediolateral GRF in IS landing conditions are partially due to the fact that the foot contact is less perpendicular to the inverted surface and increased frictions compared to the flat surface.

The reduced peak horizontal GRF in IS landing did not support what we hypothesized. Further examination of the mediolateral GRF curves suggest that although the peak medial GRFs were reduced in IS landing, the lateral GRF was actually greater in IS landing compared to FS landing (Figure 2a and c). This is coupled with greater ankle inversion motion and velocity on the inverted surface. The IS landing showed 6° greater contact inversion angle and 20° greater peak inversion compared to the FS landing. In addition, an inversion contact velocity was observed in IS landing condition compared to an eversion contact velocity in FS landing. To avoid slipping during IS landing, we placed sand paper strips on the inverted surface11. The increased friction during the landing phase causes foot fixation on the inverted surface and the downward momentum places the ankle in the extremely inverted position. The GRF vector might have actually been further away from the inversion axis creating greater external inversion moment during IS landing which must be counteracted by the greater internal eversion muscle moment. To avoid injury to the lateral ligaments due to further inversion and maintain a balanced ankle position, the ankle muscles did exhibit a greater eversion moment of the ankle during IS landing. In addition, the increased inversion angle at contact places the lateral ankle ligament complex and ankle muscles in a tauter state thus allowing the ligaments and muscles to contribute more in restricting inversion and attenuating the impact forces. The results from this study suggest that the IS landing testing protocol provides a more suitable and demanding testing protocol for investigation of ankle sprain mechanisms compared to the landing on a flat surface as it imposes greater inversion and inversion load to the ankle. Many lateral ankle sprains occur during landing onto an uneven surface from a jump which place the ankle in an extreme inverted position [16].

Our secondary hypothesis was that wearing an ankle brace would reduce the differences in GRF and ankle kinematic and kinetic variables in the two different testing protocols. The results showed that wearing a brace did not cause any significant changes in the peak vertical and horizontal GRFs in both landing surface conditions which supported the hypothesis. However, Hodgson and the colleagues [16] found a significant

面上着地使用与没有使用踝关节护具相比第一垂直的GRF峰值(趾接触)显著增加。增加的垂直GRF经常被归因于矢状面ROM的减少,这是由于脚踝护具减少了踝关节ROM[16]。在我们的研究中,踝关节护具的应用减少接触角12°,背曲ROM 8°。这些结果与由McCaw等人[17]的研究结果是一致的,他们研究也表明,与单纯着地相比,使用护具着地于平坦表面,脚跖曲接触角减少(2~4°)、背曲ROM减少(5~6°)。在支撑着地触地时和最大背曲速度也显著减少。然而,这些减少同样伴随着踝关节跖曲力矩的增加,这可能导致使用护具着地情况下垂直的GRF峰值不变。此外,我们发现使用护具后在斜面和平面着地条件下达到第二垂直GRF峰值的时间减少,表明负荷率增加,并涉及脚踝跖曲力矩的增加。这些结果与Hodgson等人[16]的研究结果相似。以评估护具对垂直GRFS的峰值及着地过程中踝关节的动力学的影响,特别是在斜面上着地的影响的研究是有限的。我们的研究结果与以前的研究结果相吻合,即脚踝护具缩短达到垂直GRF峰值时间,表明该下肢关节,尤其是踝关节,经受了增加的负荷[25]。此外,是否使用护具在GRFS峰值方面缺乏显著差异,可能与参与研究的健康受试者有关。那些患有慢性踝关节不稳定症的人可能对于踝护具有不同的反应,可能更多地依靠护具抵抗内翻负荷。有了足踝护具在着地时会减少能量的吸收[24,26]。相反地,穿着护具会从脚踝肌肉传递更大能量到腿的上端,从而增加对膝关节和髋关节的受力。对膝关节和髋关节的动力学和运动学的进一步研究可能有助于进一步解释在脚踝护具条件下GRFs峰值的结果。用于本研究的足踝护具是一个带有脚后跟捆扎系统的半刚性护具,它与其他类型的护具相比,可提供对踝关节ROM更多的限制性并可能反过来造成护具的能量吸收的负面影响。然而,护具本身可以通过自身结构消耗能量来弥补着地时能量吸收的差异。对护具是否确实有助于耗能做进一步研究与测试是必要的。

与平面着地相比,IS着地时候踝关节护具对额状面的运动学与动力学的数据有几个显著的影响。踝关节护具降低了踝关节额状面接触角以及最大内翻角。这些发现和前人的研究一致,他们的研究也显示通过踝关节护具控制着地前踝关节的位置,而减少最大内翻角[4]。踝关节护具引发的在平面和IS着地时最大外翻角速度显著降低,这很大程度上是由于踝关节外旋力矩提高造成的。这些发现与之前关于IS着地过程中的踝关节护具的作用机制的研究结果是一致的[4,10,11,19,27,28]。然而,踝关节外旋力矩提高是否是由护具造成的仍然不清晰。最终,外翻力矩上升这一现象好像与我们关于踝关节护具能够降低踝关节有关力矩的假设是不一致的。这一结果也显示,该踝关节护具(带有跟剥离系统的半刚性护具)也许能够提高踝关节构建的刚度,可以用来预防踝关节外侧扭伤。

在FS着地的时候,与不带护具时相比,护具让脚落地时处于更中间的位置,这可以造成人体重心(COG)更向着地脚内侧移动。踝关节护具不仅可以影响踝关节的移动,而且会影响更远端关节。应用踝关节护具的时候,由于踝关节被固定住,作用力会向远端转移,造成膝关节内收,以

increase in the 1st vertical GRF (toe contact) during flat surface landing with ankle brace compared to no brace. This increased vertical GRF has often been attributed to a decrease in sagittal-plane ROM due to reduced ankle ROM with an ankle brace [16]. In our study, the ankle brace application caused a reduced ankle contact angle of 12° and dorsiflexion ROM of 8°. These results are in agreement with findings by McCaw and his colleagues who also showed reductions in plantarflexion contact angle (2-4°) and in dorsiflexion ROM (5-6°) in braced landing on flat surface compared to no brace landing [17]. The contact and maximum dorsiflexion velocities are also significantly reduced during the braced landing conditions. However, these reductions of ankle kinematics were accompanied by increased plantarflexion moment, which might have led to the unchanged peak vertical GRF variables in the braced landing conditions. In addition, we observed a shorter time to the 2nd peak vertical GRF for both inverted surface and flat surface landing conditions with ankle brace, suggesting greater loading rate and that this may be also related to the increased plantarflexion moment. These findings are similar to the findings of Hodgson et al. who also observed an increased loading rate in the braced landing (on flat surface) [16]. Limited research has been conducted to evaluate the brace effects on the peak vertical GRFs and ankle joint kinetics during landing, especially on inverted surface. Our results are supported by previous findings that ankle stabilizers shorten the time to reach the peak vertical GRFs suggesting that lower extremity joints, especially the ankle joint, are subjected to increased loading with brace [25]. Furthermore, the lack of significant differences in peak GRFs with ankle brace compared to no brace conditions may be related to the healthy subjects used in our study. Those who have chronic ankle instability may react differently to test conditions and may rely more on ankle brace to resist inversion loading. Less energy absorption by the ankle plantarflexors would occur during landings with ankles stabilized [24,26]. Conversely, a greater energy transfer from ankle musculature while wearing ankle brace up to the leg would probably increase the demand on knee and hip joints in energy absorption [17]. Further examination of knee and hip kinetics and kinematics may help further explaining the results of peak GRFs in the braced conditions. Since the Element ankle brace is a semi-rigid brace with a heel strapping system, it provides more ROM restriction than other types of ankle brace [19] which may in turn negatively influence energy absorption. However, the brace itself may help dissipate energy through its own structure to make up the difference in energy absorption during braced landing. Further testing on whether braces do indeed contribute to energy dissipation is warranted.

There are several important brace effects on frontal plane kinematics and kinetics in the IS landing compared to the reg

完成能量的吸收以及平衡着地[15]。Venesky 的研究显示，当在斜面着地的时候，带护具和不带护具的关节都会有膝关节外展（外翻）力矩，这一力矩是通过侧膝关节被动结构和肌肉来对抗其内收运动[15]。对膝关节和髋关节的运动学和动力学变量的进一步研究可以提供关于斜面以及踝关节护具对整个下肢运动链着地过程变化状况。

在本研究中，踝关节护具的存在，降低了两种着地地面条件下的踝跖曲接触角和背曲 ROM。McCaw 等人[17]也报道了在带护具着地的时候，跖曲接触角和背曲 ROM 比不带护具的时候更低。在研究中，发现半刚性的踝关节护具更大程度的降低了踝关节接触角以及背曲 ROM，这种差异可能是由于着地方式的差异造成的。在 McCaw 等人的研究中，被试者是从 0.59 m 高的平台做 Step-off landing 着地动作，踝关节着地角度更倾向于背曲，在 3 个普通踝关节护具，Active 踝关节护具以及无护具着地实验条件中，平均的踝关节着地跖曲角分别为 12° 、13° 以及 15° [17]。在我们的研究中，被试者是从较低的高度（0.45 m）做不同的 drop landing（垂直脱手）着地动作，从而使踝关节在着地前更加跖曲，在 FS 和 IS 不带护具着地中，踝关节着地时的跖曲角度分别为 18.5° 和 17.9° 。Wright 等人的研究显示，触地跖曲角对扭伤的影响比触地内旋角的影响要大[29]。初始踝关节位置的区别也能影响能量的吸收，这主要是因为背屈 ROM 幅度与能量吸收量紧密相关。

4 结 论

与 FS 着地相比，IS 着地会导致较小的最大垂直和内侧 GRF、背曲 ROM、着地和最大背曲速度与跖曲力矩，但是会带来较大的内翻角度和 ROM、着地内翻角速度以及外翻力矩。这些结果显示：斜面增加了踝关节额状面的 ROM 以及踝关节的结构受力。被测试的踝关节护具降低了第二峰的垂直 GRF、踝关节着地角以及背曲角速度、最大外翻速度和跖曲速度，但是增加了 IS 着地时候的最大跖曲力矩。踝关节护具对踝关节额状面 ROM 以及受力的作用很有限。将来应该不只研究踝关节运动学和动力学，也应该研究膝髋关节的运动学和动力学，已达到对 IS 着地以及踝关节护具使用时候的整个下肢运动链的生物力学构图更深刻的了解。

ular landing. Ankle brace restricted the contact and maximum inversion angle in IS landing. These findings are supported by a previous study which showed reduced maximum inversion with ankle brace through controlling the ankle position prior to landing contact[4]. The ankle brace caused a significantly reduced maximum eversion velocity in both landing protocols. These reductions are most likely caused by the increased ankle eversion moment. These findings are supported by majority studies of ankle brace effect during inversion drop[4,10,11,19,27,28]. However, it is unclear if the increased ankle eversion moment is caused by the semi-rigid construction of the brace. Further investigation is needed to verify this result. Finally, the increased ankle eversion moment seems to contradict our hypothesis that the ankle brace may reduce the differences of ankle kinetics between braced and unbraced conditions. The results also suggest that the Element ankle brace, a semi-rigid brace with a heel strapping system, may increase the stiffness of the ankle complex which may help prevent lateral ankle sprains.

The brace application positions the foot in a less inverted and more neutral position at touchdown during FS landing and may cause the center of gravity (COG) to be moved more medially on the foot plantar surface compared with FS landing without bracing. Ankle braces not only affect ankle movement but also more proximal joint (s). With the application of the ankle brace, the ankle joint is locked and impact loading may be more likely to be transferred proximally to cause a knee adduction (varus) motion for the purpose of energy absorption and balance landing[15]. Venesky showed an existence of knee abduction (valgus) torque in both brace and no brace conditions in landing on an inverted surface, which resists the adduction motion through the lateral knee passive structures and muscles[15]. A further examination of the knee and hip kinematic and kinetic variables would provide a more comprehensive picture of landing strategy changes of the entire lower extremity kinetic chain in response to the inverted surface and application of ankle brace.

The ankle brace restricted the contact plantarflexion angle and dorsiflexion ROM in both landing conditions in the current study. McCaw and his colleagues also reported reductions in plantarflexion contact angle and dorsiflexion ROM in braced landing compared to no brace condition[17]. In our study, the semi-rigid Element ankle brace caused greater reductions of the ankle contact angle and dorsiflexion ROM. The differences may be due to the difference in the landing protocols. In the study by McCaw et al., subjects performed step-off landing from a 0.59 m platform and the initial ankle contact position was more dorsiflexed with an average contact plantarflexion angle of 12° for three common ankle braces, 13° for Active ankle brace, and 15° control condition[17]. In our study, subjects performed drop landing from a lower height (0.45 m) and the initial ankle position should be be more plantarflexed prior to contact which caused greater contact plantarflexion angle of 18.5° (no brace) in FS landing, and 17.9° (no brace) in IS landing. Wright et al. showed that the touchdown plantarflexion angle has a greater influ ence on the sprain occurrence than the touchdown supination (inversion) angle [29] .

CONCLUSIONS

IS landing induced smaller peak vertical and medial GRFs, dorsiflexion ROM, contact and maximum dorsiflexion velocities, and plantar flexion moment, but greater inversion angle and ROM, contact inversion velocity and eversion moment compared to FS landing. These results suggest that the inverted surface increased frontal-plane ankle ROM and loading of ankle complex. The ankle brace decreased the time of 2nd peak vertical GRF, contact angle and dorsiflexion velocity, and maximum eversion velocity and plantarflexion velocity, but increased maximum plantarflexion moment in IS landing. The effects of the ankle brace on frontal-plane ROM and loading of ankle complex is rather limited. Future studies should investigate not only the ankle joint kinematics and kinetics, but also the knee and hip joint kinematics and kinetics in order to provide a comprehensive profile of loading to the entire lower extremity kinetic chain during IS landing and ankle brace application.

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