



No instruction no problem: Habitual technique achieves balanced load management during two-metre parkour drop-landings

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ABSTRACT

Background: Parkour involves high-impact landings, frequently from considerable heights. Indeed, over 60% of documented injuries are sustained during landings. Efficient load management during the landing process is therefore critical for performance and injury prevention. Although traceurs (parkour athletes) have been shown to employ softer, knee-dominant landing strategies compared to untrained individuals, the influence of landing technique on joint mechanics under conditions simulating environments typically experienced in parkour remains unclear. This study aimed to examine the effects of landing instructions, habitual, soft, and stiff, on lower-limb joint dynamics during two-metre drop landings in experienced traceurs.

Methods: 14 male athletes (training age = 8.8 ± 2.4 years) performed drop landings from a two-metre platform while sagittal-plane video and ground reaction forces were recorded. Ankle, knee and hip joint moments, powers, and mechanical work were derived using 2D inverse dynamics and compared using statistical parametric mapping ($\alpha = 0.05$).

Results: Ground reaction forces frequently exceeded seven times bodyweight, displaying a consistent bimodal pattern, with peaks at ~ 9 and ~ 35 ms after ground contact. Stiff landings resulted in increased plantarflexor moments and eccentric power in comparison to habitual and soft techniques, indicating higher ankle loading. In contrast, soft landings exhibited a reduced absorption of experienced energy, resulting from decreased total eccentric work across joints.

Conclusion: These findings suggest that habitual parkour landing strategies are favourable for effective high-load management, and that verbal instructions may alter joint loading without improving overall landing mechanics. This study provides insight into impact management strategies under realistic parkour conditions and offers implications for safe skill progression in high-impact sports.

1. Introduction

Efficient energy dissipation is an integral component of many jumping sports, such as volleyball, basketball, and gymnastics, with the purpose of protecting the body from high impacts. Parkour is a unique model for the study of high-impact landings, as it is characterised by frequent landings, often from heights far above one metre. Since the sport's emergence in the late 1980s, it has rapidly gained significant popularity, primarily through social media, due to its seemingly extreme jumps and impressive heights (Pagnon et al., 2022). Despite this, research on parkour biomechanics has remained limited, particularly regarding the extreme drop heights commonly encountered in practice.

Considering that studies have reported that 64% of documented parkour injuries are sustained during landing activities (Rossheim and Stephenson, 2017; Wanke et al., 2013), further research at ecologically valid drop heights in parkour is needed to better understand factors associated with injury risk.

Parkour athletes, known as traceurs, utilise various strategies to manage landing impact. These include stepping out to maintain forward momentum, employing a four-point landing to disperse energy through both the legs and arms, or rolling to redirect vertical energy to horizontal energy (Croft and Bertram, 2017; Dai et al., 2020). Nevertheless, in a multitude of landings, often executed on narrow edges or corners, traceurs are required to “stick” the landing in a stable and controlled

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manner. In the sport, this is termed a “precision” landing and is characterised by initial ground contact with the forefoot, maintaining the heels off the ground throughout the landing process, counterbalancing with the arms, and absorbing impact energy primarily through lower-limb motion without evasive steps (Maldonado et al., 2017; Puddle and Maulder, 2013). The absence of heel contact alters the mechanical interaction between the foot and the ground compared with traditional heel-contact landings. While this interaction has yet to be investigated explicitly, it may involve greater reliance on active control of the ankle joint through plantarflexor function, potentially influencing how mechanical energy is transferred and dissipated throughout the lower limbs. Therefore, parkour precision landings provide an ideal case for studying energy absorption, inter-joint coordination, and landing control under high mechanical loads and demands.

As demonstrated in previous research, traceurs exhibit softer landings with a greater lower-limb range of motion when compared to recreationally active athletes (Maldonado et al., 2018; Standing and Maulder, 2015). Their adoption of knee-dominant strategies has been shown to contribute over 50% of the total joint work during absorption, in contrast to the ankle-dominant strategies observed in recreationally active athletes. The modification of drop-landing technique through verbal instructions, a common practice in parkour, has been demonstrated to elicit changes in lower-limb kinematics and joint dynamics. The effectiveness of such instructions may partly relate to their ability to direct an athlete's attentional focus, which can influence movement execution and coordination (Porter et al., 2013; Wulf, 2013). One common example in parkour is the instruction to adopt a stiffer landing strategy when the intention is to “stick” a landing, similar to techniques employed in gymnastics. In recreational athletes, such stiff landings resulted in increased peak vertical ground reaction forces (vGRF), peak ankle plantarflexor, and knee extensor moments. In addition, ankle range of motion has been negatively associated with total energy expenditure during landing tasks (Xu et al., 2024), suggesting that alterations in lower-limb excursion may influence mechanical energy management. These findings highlight that modifications to landing strategy can alter the distribution of mechanical demands and transfer of load across the lower limbs, with the stiff landing strategy increasing the relative importance of the ankle joint in absorbing energy (Devita and Skelly, 1992; Verniba et al., 2017; Zhang et al., 2000). Conversely, softer landings performed by recreational athletes have been shown to be associated with greater knee and hip range of motion, lower peak vGRF, and longer impact durations. These changes result in decreased peak extension moments of the lower-limbs and greater reliance on the knee extensors for energy absorption, potentially reducing injury risk, particularly on the level of the ankle plantarflexors (Devita and Skelly, 1992; Verniba et al., 2017; Zhang et al., 2000). However, whether the biomechanical consequences of this strategy observed in recreational athletes translate to experienced traceurs performing parkour-specific landings remains unknown. To date, no studies have examined joint dynamics and energy distribution during landings from heights that simulate realistic parkour scenarios. Moreover, it remains unclear how these landing strategies and associated verbal instructions scale to the extreme loading conditions typically experienced by traceurs. Understanding how athletes highly skilled in landing tasks manage extreme impacts from sport-specific heights can inform performance and injury prevention metrics not only within that sport itself but can also shed light on general mechanical adaptability of the lower-limbs under extreme eccentric loading. Additionally, verbal instructions may disrupt the automated habitual landing technique, thus providing practical information for coaching purposes.

To this end, we investigated sagittal plane lower-limb joint kinematics, kinetics, and dynamics of highly experienced traceurs performing drop landings off a two-metre height according to three landing instructions. The instructions aimed to modify the landings resulting in habitual, soft and stiff techniques. We hypothesised that the different verbal instructions would lead to altered joint stiffness and dynamics.

Specifically, we expected that the soft landings would be performed with a greater knee and hip joint range of motion, thus allowing for a longer impact duration. Furthermore, we expected the increased impact duration and joint range of motion to lead to decreased joint stiffness, joint extension moments and powers and increased total mechanical work. Contrarily, we hypothesised increased joint stiffness as well as increased joint extension moments and powers during the stiff landings, thus reducing total mechanical work.

2. Methods

2.1. Participants

An a priori power analysis (G*Power, v3.1.9.4), in accordance with the reported results in the studies of Devita and Skelly (1992) and Maldonado et al. (2018), indicated that a minimum of ten participants would be necessary to detect a medium effect of $f = 0.35$ with a power of 80% at an alpha level of $p < .05$. A correlation among repeated measures of $r = 0.70$ was expected, reflecting the anticipated consistency of performance across conditions among the experienced participants. Thus, 14 experienced male parkour participants (age: 23.9 ± 3.0 y, training age: 8.8 ± 2.4 y, body mass: 77.3 ± 6.6 kg, height: 182.4 ± 3.8 cm) were recruited from local sports clubs in Bochum, Germany. The participants were healthy, with no serious lower-limb injuries and were required to subjectively assess two-metre drop landings as being no more than a five on the rate of perceived exertion scale (Zourdos et al., 2016).

A within-subject repeated-measures cross-sectional design was used to evaluate participants' kinematic and kinetic parameters of the hip, knee, and ankle joints during drop landings performed from a two-metre height, across three verbal instruction conditions. The experimental procedure was carried out at the MoveLab biomechanics laboratory of the Faculty of Sport Science at Ruhr-University Bochum, Germany. Participants took part in the study voluntarily after providing written informed consent. All procedures were approved by the local ethics committee (Ruhr-University Bochum, Sports Faculty).

Only male participants were recruited as at the time of the experiment's execution a disproportionate amount of parkour participants were demonstrated to be male. This choice is supported by the percentage of male participants seen elsewhere: 78.3%, 87.7%, 91.3%, 94% and 96% from Grosprêtre and Khattabi (2022), Grosprêtre and Lepers (2016), Da Rocha et al. (2014), Rossheim and Stephenson (2017), and Wanke et al. (2013), respectively.

1.1. Experimental Setup

Vertical GRFs were recorded using a ground-embedded piezoelectric force platform (Type 9287 A, 90×60 cm, Kistler Instrumente AG, Winterthur, Switzerland) sampling at 1200 Hz. To indicate a point of landing to participants, a 2 cm thick line using orange tape was affixed along the middle of the force plate. The drop height was achieved using a custom-built scaffold with a height of 196.7 cm, placed at a distance of 120 cm from the orange tape as displayed in Fig. 1, SETUP. One high-speed video camera (Casio EXILIM EX-F1, Casio Computer Co., Ltd., Tokyo, Japan) sampling at 300 Hz was positioned perpendicular to the force platform (to the right of the participants) at a distance of 270 cm to record sagittal plane movement. The resultant view was such that the lower edge of the camera field of view ended 20 cm before the force plate started. Five white, round markers (white tape, diameter: 25 mm) were attached to five lower-limb bony landmarks (Fig. 1, PREP). Participants were instructed to wear the shoes they would typically use for parkour training.

2.2. Experimental procedure

To record bodyweight participants were instructed to adopt a quiet stance posture on the force platform for five seconds. This was followed

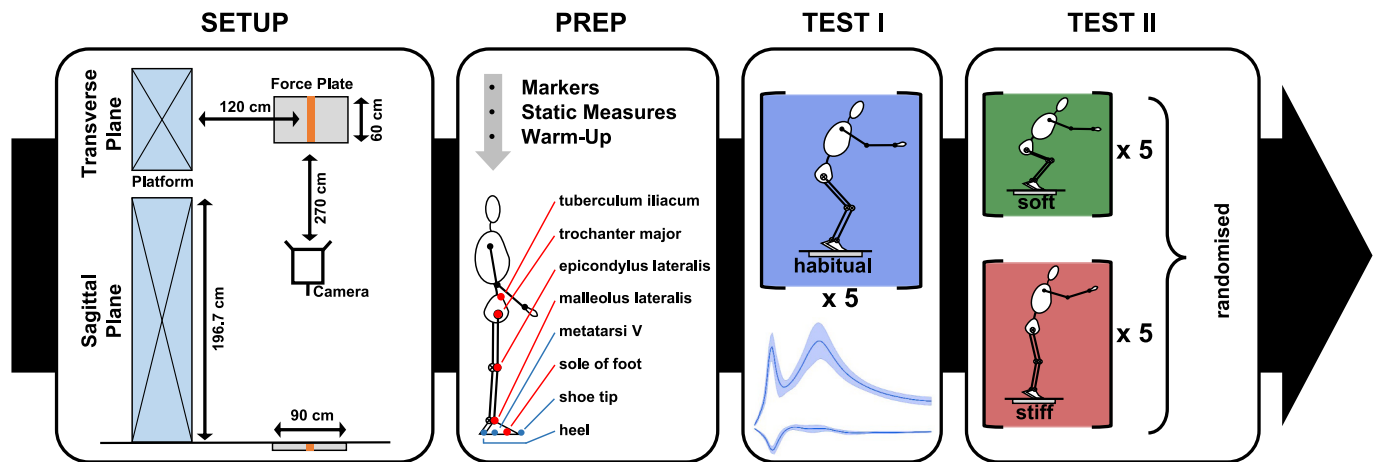


Fig. 1. Experimental setup and procedure. **SETUP:** The experimental setup illustrated from above (transverse plane) and the side (sagittal plane). The distance between the 196.7 cm platform and the middle of the 90 × 60 cm force plate (orange band) was 120 cm. The video camera was placed 270 cm from the middle of the force plate, on the participants' right side. **PREP:** Marker placement with anatomical marker positions displayed as red spheres and virtual marker positions displayed as blue spheres, followed by static measures and the warm-up. **TEST I:** Habitual landings and their respective vertical and horizontal ground reaction forces, with mean normalised waveforms and shaded standard deviation envelopes. **TEST II:** Soft and stiff landings were performed in a trial-randomised order after the habitual block (figure kinematics exaggerated for clarity). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by a standardised 15 min parkour specific warm-up. To allow for familiarisation two drop landings without further constraint were performed before the testing. Then participants were instructed to stand with the balls of the feet on the edge of the scaffold, lower the glutes onto the heels, lift the heels, drop away from the platform with both feet simultaneously, perform a parkour precision landing, and not leave the landing position until signalled to do so by the principal investigator. Afterwards one landing was performed in accordance with the instructions mentioned above. Each participant then performed 15 drop landings, based on three distinct verbal instructions: habitual, soft, or stiff. Habitual landings were instructed to be completed naturally, without modifying the participants' habitual precision landing technique. Soft landings were instructed to be executed by absorbing the force at landing and bending the knees and hips as much as still comfortable. Stiff landings were specified to be carried out by resisting the force at landing and bending the knees and hips as minimally as possible.

All five habitual landings were performed as a block first to avoid influencing the natural landing biomechanical patterns (Fig. 1, TEST I). Soft and stiff landings were performed subsequently in trial-randomised order (Fig. 1, TEST II). All drop landing techniques were performed as previously outlined and further demonstrated to all participants by the principal investigator. Drop landings were repeated at the end of the randomised order if any the following predefined criteria was met: the take-off was performed with a vertical upwards momentum, the landing position was not kept until the signal came (i.e. stepping away from the landing position), the participant lost balance, or the investigator judged the landing to not adhere to parkour precision standards. A rest period of three minutes was given between each landing trial.

2.3. Data analysis

In total 210 drop landings were recorded, of which five could not be digitised due to marker obstructions. Marker positions for all trials were digitised with Kinovea software (v2023.1.1), and camera coordinate system was calibrated for each recording. The five applied markers were tracked for the entire landing phase, starting 50 ms before landing and ending 400 ms after landing. Markers were initially tracked automatically by the system and manually checked after every trial frame-by-frame. Following digitisation of all markers, files were exported for data analysis in Python (v3.13.4) using custom-written scripts (available

at <https://github.com/kevinsoter/IMPACT-Study>).

A scaling file was created for each subject based on manually measured foot length, distance between anterior tip of the shoe and the fifth metatarsal marker, the vertical height of the malleolus lateralis marker, and segment lengths of the shank, thigh and hip between the corresponding marker pairs. The raw marker positions were passed through a custom-written two-dimensional inverse kinematics solver (Sommer and Miller, 1980; Winter, 2009), which utilised the scaling file to fit a subject-specific rigid body model to the raw data following a least squares approach. The outcome was solved and corrected marker positions, interpolated to the force plate sampling frequency using a cubic spline. Virtual markers were added to represent: (1) the sole of the foot, (2) the anterior tip of the shoe, and (3) the posterior aspect of the heel. All virtual markers were expressed relative to the local foot coordinate system and updated continuously according to the instantaneous orientation of the foot segment. Thereafter, ankle, knee and hip joint angles, velocities and accelerations were calculated according to trigonometric relationships. The marker and kinematic data, together with the force data, were subsequently passed through a custom-written two-dimensional inverse dynamics script based on Newton-Euler equations (Robertson, 2014; Winter, 2009) and established segment inertia properties (De Leva, 1996) to obtain joint dynamics for the ankle, knee and hip.

The filtering process was implemented with particular care. Drop landings off two metre heights produced vGRF trajectories characterised by two peaks approximately 9 ms and 35 ms after ground impact. Pilot testing revealed that filtering kinematics and kinetics using the same low-pass cut-off frequency between 20 and 50 Hz, as prevalent in the literature (Harry et al., 2022; Van den Bogert and De Koning, 1996) attenuated the first occurring vGRF peak by 40 to 65%. Thus, according to Edwards et al. (2011), neither kinematic nor kinetic data were filtered during data processing. Only after the process of inverse dynamics, the resulting joint moments were filtered using a zero-phase shift, low-pass, fourth-order Butterworth filter. This approach enabled the use of joint specific cut-off frequencies as pilot data revealed a progressive decrease in movement frequency from distal to proximal joints. Hence, the cut-off frequencies for individual joints were determined by residual analysis (Winter, 2009) between 1 and 100 Hz on joint angle data calculated from raw marker data of all trials of four randomly selected subjects. Accordingly, the resulting cut-off frequencies were 28 Hz for the hip joint, 37 Hz for the knee joint and 43 Hz for the ankle joint.

Subsequently, the joint power was calculated as the scalar product of filtered joint moments and filtered joint velocities. In addition, the cumulative mechanical joint work was calculated by integrating the joint power signal over time. Lastly, the period of main force production was identified as the primary phase of interest. This phase will be referred to as the impact phase, and, in line with Devita and Skelly (1992), was defined as the time between initial ground contact (vGRF >50 N) and the subsequent local minimum or quasi-stable value in vGRF following the two characteristic force peaks (Fig. 2).

One-dimensional trajectories of the filtered variables ankle, knee and hip joint moment, power, and total mechanical work across all three joints were extracted for the impact phase, time-normalised across this phase, and averaged for each individual subject across landing technique prior to statistical analysis. Discrete variables of interest were the two vGRF peaks and the respective occurrences in time, the ankle, knee and hip joint range of motion over the entire landing, the peak joint velocities, the joint stiffness, calculated as the peak joint moment divided by the joint range of motion, and the total and percentual (of total) eccentric mechanical joint work performed over the impact phase.

2.4. Statistical analysis

Statistical analyses on discrete data were performed using JASP software (v0.16.4; JASP Team, 2022) with a significance level of $p < .05$. One-way repeated-measures ANOVAs were conducted for the variables ankle, knee, and hip joint stiffness, and ankle, knee, and hip percentual energy contribution across the factor landing technique (habitual, soft, and stiff). In addition, continuous one-dimensional trajectories were statistically analysed in Python using the spm1d library (v0.4.18; Todd Patakey) for statistical parametric mapping (SPM) with a significance level of $p < .05$. One-way repeated-measures ANOVAs were conducted for the variables ankle, knee, and hip joint moments, ankle, knee and hip joint powers, and total work performed across the factor landing

technique (habitual, soft, and stiff). For significant omnibus analyses in both discrete and continuous analyses, further post hoc tests with Bonferroni corrections were performed. Omnibus effect sizes were reported as partial eta squared (η_p^2) with values ≥ 0.10 , ≥ 0.25 , and ≥ 0.40 indicating small, medium, and large effects, respectively (Cohen, 2013). To better reflect the investigated sample population of experienced parkour athletes, post hoc effect sizes were reported as Cohen's d and treated as highly trained according to Rhea (2004) with values ≥ 0.25 , ≥ 0.5 , and ≥ 1.0 indicating small, moderate, and large effects, respectively. Effect sizes corresponding to significant SPM omnibus and post hoc results are reported for the peak F and t statistic values, respectively.

3. Results

The two-metre drop landings resulted in high mechanical demands on the lower-limbs, with peak vGRFs exceeding seven times bodyweight and impact durations of approximately 100 ms. Stiff landings produced the highest vGRF peaks, while habitual and soft landings showed similar peaks. Timing of both peaks was consistent, with the first peak occurring less than 10 ms after ground contact and the second peak occurring after approximately 35 ms. All landing types induced eccentric peak joint velocities in excess of 3300 deg./s, 1600 deg./s, and 2200 deg./s in the ankle, knee, and hip joints, respectively. Detailed descriptive data to further illustrate the drop landings are reported in Table 1 with joint kinematics being detailed in Supplementary Material Fig. I.

Verbal instructions affected joint stiffness in the ankle ($F(2,26) = 13.321$, $p < .001$, $\eta_p^2 = 0.506$), knee ($F(2,26) = 14.408$, $p < .001$, $\eta_p^2 = 0.526$), and hip ($F(2,26) = 5.510$, $p = .010$, $\eta_p^2 = 0.298$). Post hoc analyses revealed increased ankle and hip joint stiffness during stiff landings (all $d > 0.47$), whereas knee joint stiffness was reduced during soft landings (both $d < -0.74$); Supplementary Material Table I).

Continuous analyses on joint moments and powers with respective main effects are shown in Fig. 3 and Supplementary Material Table II,

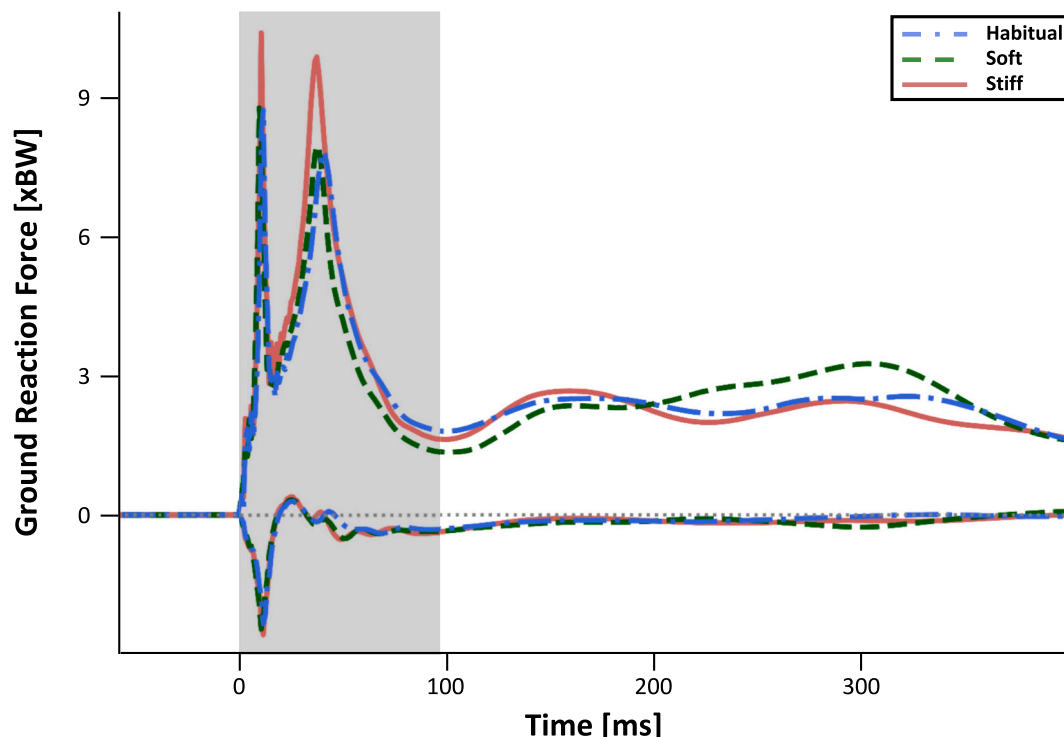


Fig. 2. Impact phase determination. Vertical and horizontal ground reaction forces from one representative participant expressed as multiples of bodyweight (x BW) per time (ms). The impact phase, shaded in grey, and representing the approximate impact phase duration for all three landing techniques, was determined from ground contact (vGRF >50 N) to the subsequent local minimum or quasi-stable value in vGRF following the two characteristic force peaks. Ground contact is delineated at time 0 ms with negative times indicating the freefall drop prior to landing. Negative horizontal GRF signals indicate anterior force application. 0 x BW indicates the empty force plate.

Table 1

Drop landing descriptive data for all subjects ($n = 14$). Summary of peak vertical ground reaction forces (vGRF), the timing of those peaks, the duration of the main impact phase, joint range of motion (RoM), and eccentric peak joint angular velocities, joint stiffness and performed eccentric work for all landing techniques. Values provide an overview of the mechanical demands associated with habitual, soft, and stiff drop landings from two metres. Decimal precision was selected according to the magnitude of each variable.

Variable	Unit	Joint	Mean $\pm$ SD		
			Habitual	Soft	Stiff
1st vGRF Peak	N/kg	–	74.4 $\pm$ 9.1	75.4 $\pm$ 10.8	89.6 $\pm$ 16.3
2nd vGRF Peak	N/kg	–	75.5 $\pm$ 16.1	74.7 $\pm$ 17.7	96.1 $\pm$ 18.4
1st vGRF Peak Timing	ms	–	9.6 $\pm$ 1.3	9.3 $\pm$ 1.3	9.2 $\pm$ 1.6
2nd vGRF Peak Timing	ms	–	36.7 $\pm$ 4.3	35.3 $\pm$ 4.4	33.7 $\pm$ 4.8
Impact Phase Duration	ms	–	101.9 $\pm$ 14.4	97.6 $\pm$ 13.2	95.9 $\pm$ 18.4
		Ankle	54.7 $\pm$ 0.4	53.5 $\pm$ 4.1	54.8 $\pm$ 5.1
Joint RoM	deg	Knee	117.1 $\pm$ 12.8	124.0 $\pm$ 11.1	104.4 $\pm$ 12.6
		Hip	73.6 $\pm$ 25.4	72.7 $\pm$ 23.3	65.4 $\pm$ 21.3
		Ankle	3366.1 $\pm$ 433.9	3372.5 $\pm$ 512.4	3604.1 $\pm$ 503.7
		Knee	1642.7 $\pm$ 178.6	1681.6 $\pm$ 198.0	1707.4 $\pm$ 172.7
Peak Joint Velocity	deg/s	Hip	2257.3 $\pm$ 736.7	2423.4 $\pm$ 694.2	2242.0 $\pm$ 536.9
		Ankle	0.135 $\pm$ 0.022	0.135 $\pm$ 0.026	0.155 $\pm$ 0.026
		Knee	0.053 $\pm$ 0.010	0.044 $\pm$ 0.010	0.057 $\pm$ 0.014
		Hip	0.163 $\pm$ 0.062	0.174 $\pm$ 0.079	0.200 $\pm$ 0.090
Joint Stiffness	Nm/kg/deg	Ankle	38.2 $\pm$ 4.7	40.2 $\pm$ 5.7	42.8 $\pm$ 5.0
		Knee	35.2 $\pm$ 4.2	32.3 $\pm$ 6.3	30.5 $\pm$ 8.0
Eccentric Work	%of total	Hip	26.5 $\pm$ 6.2	27.5 $\pm$ 7.5	26.7 $\pm$ 8.4

corresponding post hoc results are displayed in Fig. 4 and Supplementary Material Table III. Analyses on joint moments demonstrated that verbal instructions mainly affected the ankle joint. Significant differences in ankle plantarflexion moments started before the first vGRF peak and lasted until the second vGRF peak tapered off. These differences were driven by the stiff landings exhibiting greater plantarflexion moments than both soft and habitual landings (both $d > 1.58$). For eccentric joint power, verbal instructions were shown to elicit significant differences in the ankle and hip joint. Ankle power differed between instructions across two distinct periods of the impact phase. Stiff landings exhibited greater eccentric ankle plantarflexion from the first vGRF peak up until the trough between peaks compared to both soft and habitual landings (both $d > 1.39$). Throughout the occurrence of the second vGRF peak, the stiff landings exhibited increased concentric plantarflexion power compared to habitual landings ($d = -1.35$). Conversely, hip joint power differed for only a short period just after initial ground contact, with the post hoc analysis revealing a decrease of the eccentric joint power from habitual to soft landings ($d = -1.30$).

Lastly, total joint work (cumulative energy across all three joints) was affected by the verbal landing instructions for large portions of the impact phase, as depicted in Fig. 5A. Traceurs dissipated less energy in soft landings than in stiff and habitual landings (Fig. 4; both $d > 1.24$). On the individual joint-level, percentual eccentric energy absorption (i. e. work performed) exhibited significant effects for the ankle joint ($F(2,26) = 15.486, p < .001, \eta_p^2 = 0.54$) and knee joint ($F(2,26) = 5.284, p = .012, \eta_p^2 = 0.289$), with no effect at the hip joint ($F(2,26) = 0.395, p = .678, \eta_p^2 = 0.029$). Post hoc analyses (Fig. 5B; Supplementary Material Table I) indicated greater ankle contribution during stiff landings as compared to habitual and soft landings (both $d > 0.51$), whereas the

knee joint absorbed less energy during stiff than habitual landings ($d = 0.75$).

4. Discussion

The present investigation was the first to assess lower-limb dynamics and kinetics during two-metre drop landings performed by experienced traceurs. This design was hence able to highly ecologically simulate the high-impact loading conditions encountered in parkour more closely than any previous research. Furthermore, it enabled us to compare the effects of three verbal instructions, habitual, soft, and stiff, on the resulting joint mechanics. Despite high mechanical demands, all traceurs exhibited controlled and well-coordinated decelerations across all landing techniques, resulting in qualitatively similar joint moment and power trajectories. This control emphasised the athletes' high skill level. However, the habitual technique resulted in significantly lower eccentric ankle plantarflexion moments compared to the stiff landing, while allowing for greater total eccentric work across the lower limbs than the soft landing technique.

Throughout the main impact phase of two-metre drop landings, the joint moment and power trajectories demonstrated a distinct pattern of coordinated redistribution of mechanical demands across the lower limbs during impact absorption. The ankle and hip initially generated eccentric moments, whereas the knee briefly exhibited concentric flexion immediately following ground contact. This transient response, which was observed consistently across participants, may reflect the active repositioning of the lower limb during the initial impact response, likely caused by participants contacting the ground with the knee positioned posterior to the ankle. It was limited to the first few milliseconds after ground contact before rapidly transitioning to eccentric knee extension, which made up the predominant knee strategy during the main energy absorption phase. Given that the majority of jumps and drop landings in parkour involve a certain degree of horizontal distance, this was considered unavoidable.

Consequently, the ankle and hip served to counterbalance the early concentric knee flexion. The transition from concentric knee flexion to eccentric extension coincided with a decrease in eccentric ankle plantarflexion and hip extension power, reflecting a greater importance of the knee joint for the energy dissipation during the period of force application associated with the second force peak.

The present study demonstrated general agreement in trajectories of lower-limb moments and powers with previous literature. However, peak joint moments and powers were found to be drastically increased. Those increases are attributable to the difference in height from between 40 and 100 cm to two metres and can be explained by the elongated duration of vertical acceleration from gravity (Devita and Skelly, 1992; McNitt-Gray, 1993; Yeow et al., 2011; Zhang et al., 2000). To that end, the peak vGRF increased in relation to drop height, reaching values between three and six times higher than studies on traceurs performing landings below one metre height (Maldonado et al., 2018; Puddle and Maulder, 2013). Similarly, peak extension moments exhibited by the ankle, knee, and hip joint of traceurs were increased in comparison to drop landings from 60 cm by four, three, and six times, respectively. This effect was even more pronounced on the eccentric power, as the peaks for the ankle, knee, and hip joint increased by nine, five and eight times, respectively. Hence, demonstrating that even experienced athletes who might be considered experts in the task of landings cannot avoid high mechanical joint loading. In fact, the extreme ankle joint eccentric powers highlighted traceurs' particular and great capability for eccentric contractions of the lower limbs, previously shown during sport unspecific tasks (Grosprêtre and Lepers, 2016).

Previous studies investigating lower drop heights of up to one metre have reported increased eccentric plantarflexion moments accompanied by greater reliance on the ankle for energy dissipation in stiff landings (Devita and Skelly, 1992; Zhang et al., 2000). In the present study, stiff landings also increased the mechanical stress on the plantarflexor

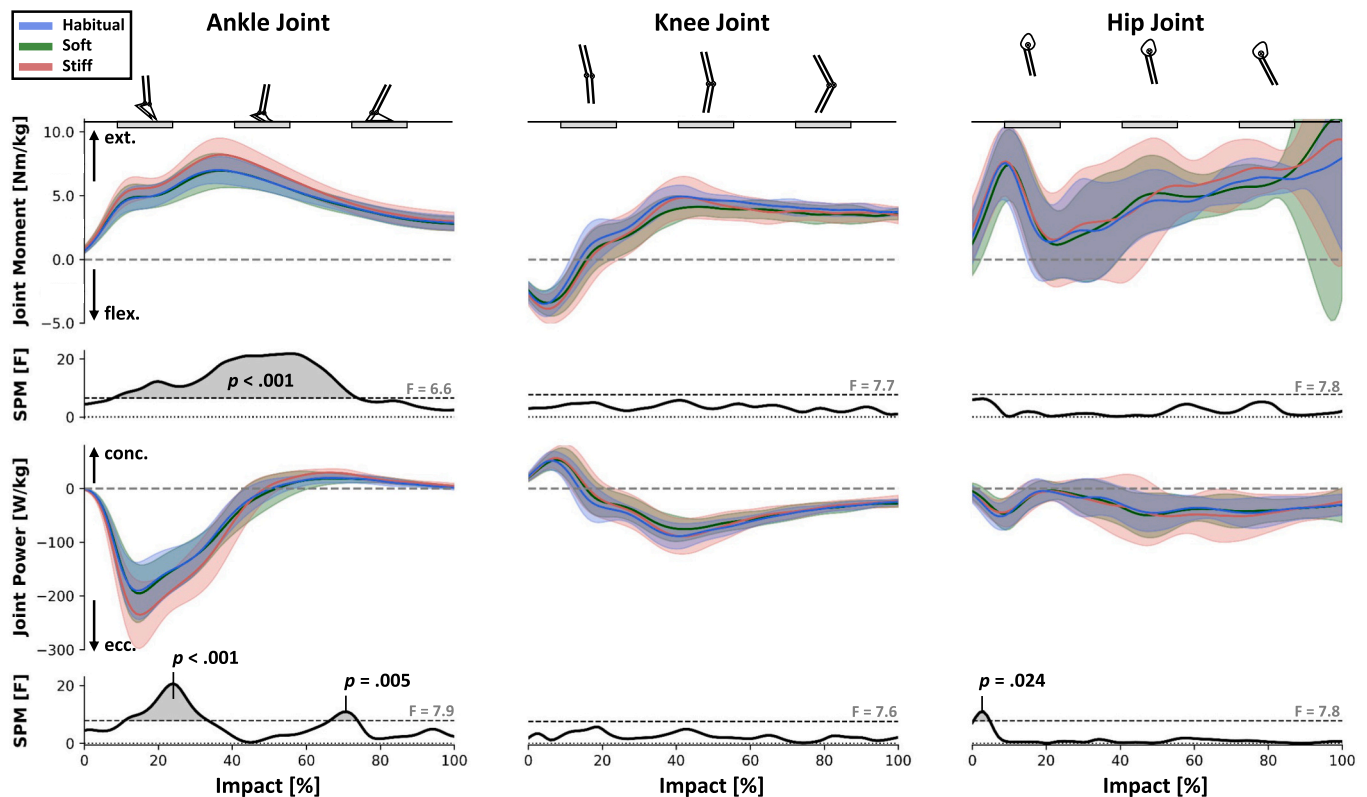


Fig. 3. Continuous mean normalised waveforms with shaded standard deviation envelopes of all subjects ($n = 14$) and SPM[F] map plots associated with joint moments and joint powers for each joint, as functions of normalised time across the impact phase (Impact [%]). Shaded grey areas on the SPM[F] maps indicate significant suprathreshold clusters, with the resulting cluster-level p -value. Respective SPM[F] map critical F-value threshold delineated by a dashed grey line. Ext. (extension/ankle plantarflexion); flex. (flexion/ankle dorsiflexion); conc. (concentric); ecc. (eccentric).

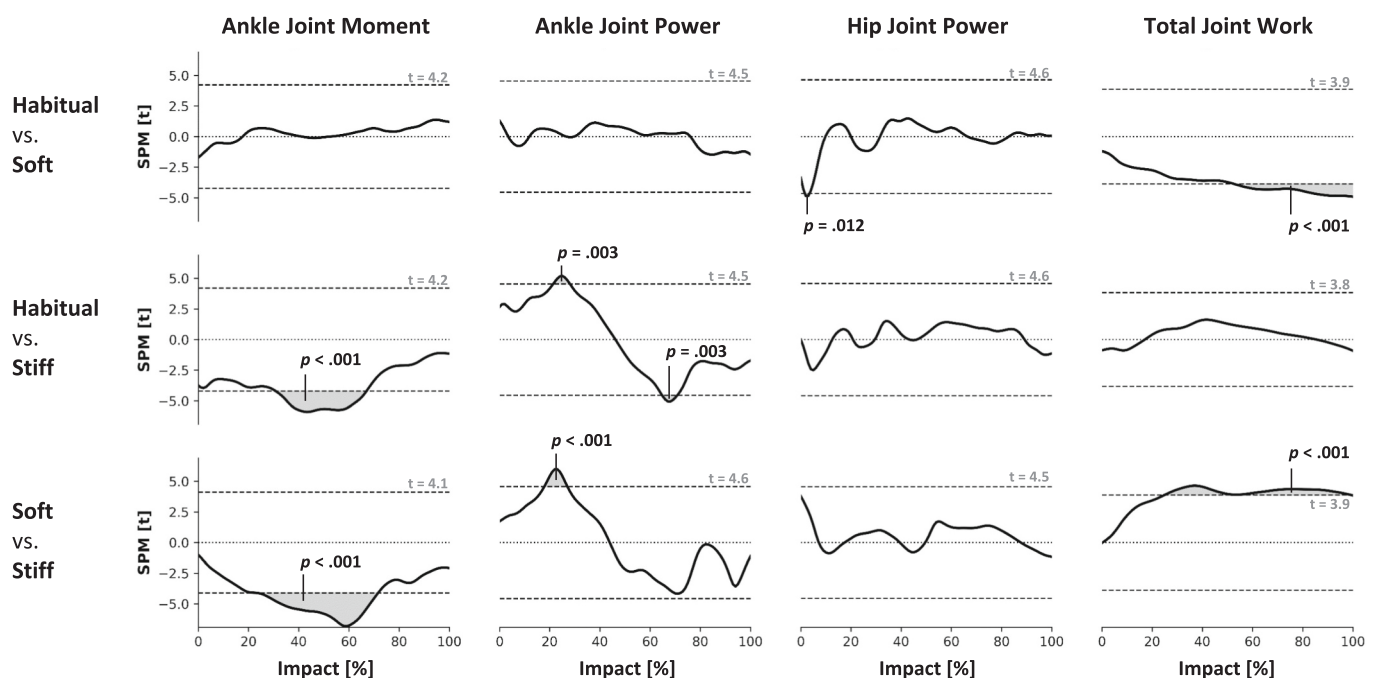


Fig. 4. Post hoc SPM[t] map plots associated with comparisons of ankle joint moments and powers, hip joint powers, and total joint work between all verbal instruction techniques, as functions of normalised time across the impact phase (Impact [%]). Shaded grey areas indicate significant t -test ranges with the resulting cluster-level p -value. Respective SPM[t] map critical t -value threshold delineated by a dashed grey line.

musculature by exhibiting peak moments 16% higher and eccentric powers 23% higher than during soft and habitual landings. Furthermore,

stiff landings elicited a shift in eccentric work towards the ankle, reducing the relative contribution of the knee and thereby shifting the

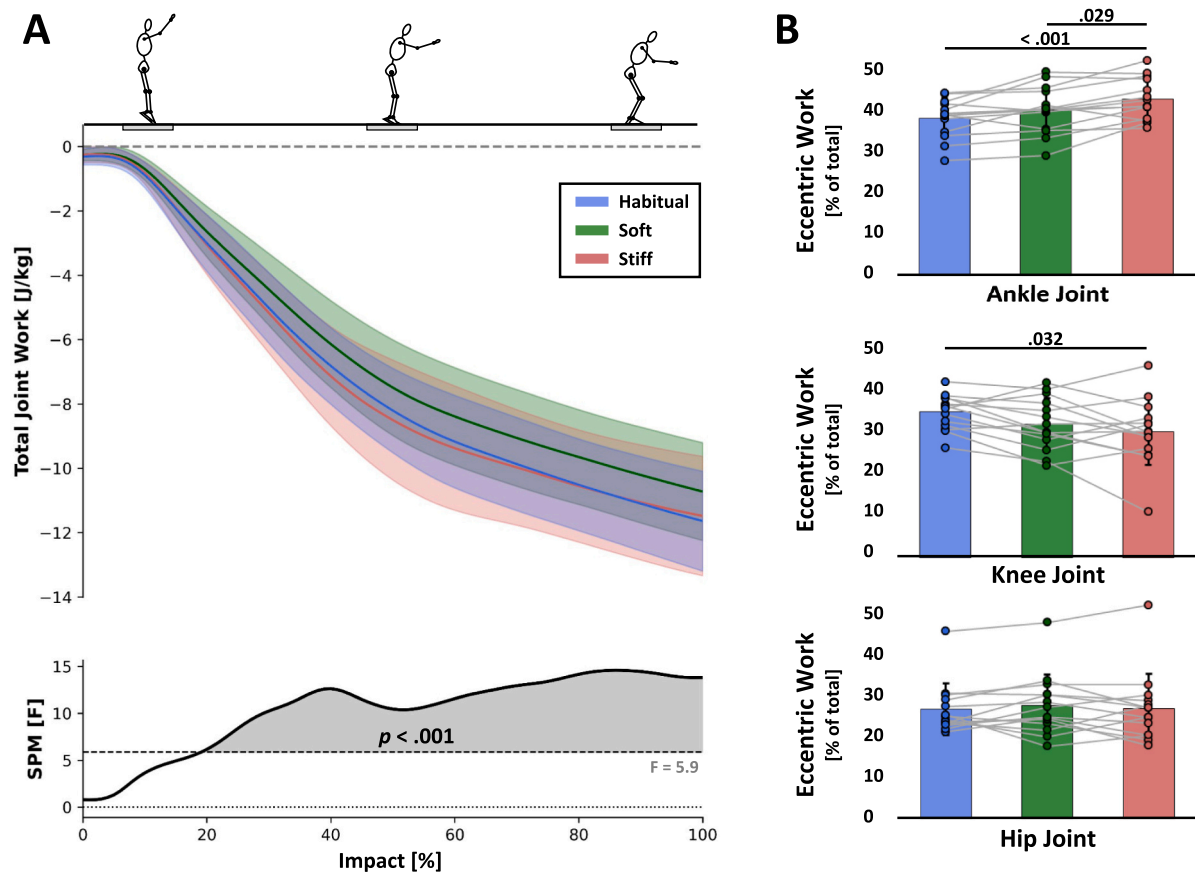


Fig. 5. Mechanical work performed at and across ankle, knee and hip joints of all subjects ($n = 14$). A: Continuous mean normalised waveforms with shaded standard deviation envelopes and the SPM[F] map plot associated with cumulative total work across all three joints, as a function of normalised time across the impact phase (Impact [%]). B: Bar plots with individual data points represent the discrete post hoc comparisons of percentual (of total) eccentric work at the joint and verbal instruction level. Grey lines connecting data points indicate within-subject changes across landing techniques.

energy absorption strategy towards greater ankle dominance. Previous studies identified the soleus muscle as one of the main contributors to force generation and energy absorption during single-leg landings and as the dominant contributor among plantarflexors (Maniar et al., 2022). Consequently, the increased ankle joint demand observed during stiff landings may reflect greater eccentric loading of the soleus muscle. Accordingly, a stiff landing technique may be applicable as a training tool, especially from lower drop heights, to increase eccentric plantarflexor loading while keeping the total kinetic energy more manageable. Furthermore, eccentric training under long muscle lengths has been linked to increased fascicle length in the form of sarcomerogenesis (Bizet et al., 2025; Pincheira et al., 2022). However, no differences in total range of motion were observed between techniques in the present study. Therefore, the stiff technique did not provide a distinct advantage over habitual landings with respect to inducing beneficial eccentric overload adaptations. Thus, despite the notable eccentric capacity of traceurs, increasing the mechanical demand at the ankle during drop landings might not be advisable, particularly when considering the already high baseline loading due to the experienced heights in parkour. Given the repetitive and high-impact nature of parkour, such increased reliance on the ankle during stiff landings may elevate the risk of overuse or acute injury at the ankle joint level with no practical performance enhancement effect.

On the other hand, a verbal instruction to perform soft landings could be expected to provide benefits by increasing lower-limb joint range of motion, prolonging loading durations and consequently lowering peak vGRF and peak joint loading. Previous studies have shown that soft landings, from heights up to one metre, are associated with increased knee and hip range of motion, longer impact durations,

and elevated eccentric work, thus enabling more effective energy dissipation through active muscular structures (Devita and Skelly, 1992; Zhang et al., 2000). However, in the present study, traceurs did not appear to benefit from such alterations. Indeed, the total duration of the impact phase in habitual landings, of 102 ms, was slightly longer than in soft landings. Additionally, soft and habitual landings exhibited similar moment and power patterns across all joints throughout the entire impact phase. This strong similarity was likely linked to the timing of the first vertical force peak, which occurred within 10 ms of ground contact and thus relied entirely on muscle pre-activation rather than reflexive responses (Santello, 2005). Given that spinal reflexes at the ankle need approximately 30 ms (Lyle et al., 2022; Soter et al., 2025), total energy absorption during the initial impact phase was also equivalent between all three landing techniques. After 20% of the impact phase, however, the soft landing condition demonstrated a distinct decline in eccentric work relative to both habitual and stiff conditions. Given that spinal reflexes may contribute to muscle activity at this stage (Santello, 2005), the reduced eccentric work suggested that traceurs may have lost some capability to actively control joint deceleration in response to the soft instruction. This likely led to greater reliance on passive tissue loading (akin to a “falling through” movement), potentially increasing the injury risk to ligaments, cartilage, and other non-contractile structures. Thus, while softer landings may seem advantageous in lower heights and non-parkour specific scenarios, they may inadvertently shift energy absorption away from active muscular contribution, reducing control and raising injury susceptibility when performed from considerable heights. It should be noted that, in accordance with previous literature, the present study employed a combination of internal and external verbal instructions to elicit alterations in landing technique. Previous studies

have demonstrated that exclusively external cues to induce soft landings can reduce vGRF and exhibit smaller sagittal knee extension moments in drop landings (Slovák et al., 2024), while also increasing total eccentric work performed across lower-limb joints (Harry et al., 2019). More broadly, externally focused instructions have been shown to enhance movement performance even in highly skilled populations (Porter et al., 2013), an effect commonly attributed to the ability of external cues to effectively engage automatic motor control instead of constraining the athlete's habitual technique (Liu et al., 2024). Although, the mixed verbal instructions utilised in the present study successfully induced the desired effect on a stiffness level, the use of exclusively external cues may produce more favourable adaptations in soft landings even in experienced traceurs.

Overall, verbal instructions to adopt soft or stiff landing strategies altered the distribution of mechanical demands without demonstrating biomechanical benefits compared with the habitual strategy. Habitual drop landings in highly experienced traceurs may already represent a biomechanically favourable solution, suggesting that acute technique modifications through verbal instructions should be introduced cautiously. This does not imply that coaching is unnecessary, but rather that acutely altering an already well-established landing strategy may be counterproductive. Instead, technical modifications should be implemented progressively and evaluated over longer periods of practice rather than expecting immediate improvements following simple verbal cues. Indeed, coaches may still use stiffer landing cues strategically to increase ankle plantarflexor loading during progressive training (for example at lower drop heights), whereas soft landing cues as implemented in the present study cannot be recommended for experienced traceurs performing two metre drop landings because they reduced actively absorbed energy without evident biomechanical benefit. As the present findings, particularly for soft landings, differ from those reported in recreational athletes, the apparent advantages of the habitual landing strategy should not be generalised across populations. Furthermore, whether this strategy remains favourable across different task demands in experienced traceurs requires further investigation. These findings emphasise the significance of sport-specific training and highlight the potential consequences of modifying well-established motor patterns without a clear biomechanical or performance benefit.

5. Methodological limitations

The present study employed a two-dimensional analysis, a methodology which was justified by the predominantly sagittal nature of vertical drop landings. We observed that $89 \pm 1.0\%$ and $9.7 \pm 0.9\%$ of the total ground reaction force impulse were generated in the vertical and anterior-posterior directions, respectively, which is in line with previous research (Simpson et al., 2018). Additionally, Yeow et al. (2011) observed that over 87% of lower-limb power and 90% of energy dissipation occurred in the sagittal plane during 60 cm drop landings. Given the considerable vertical displacement and horizontal travel distance involved in the landings investigated, it is reasonable to assume that sagittal plane dynamics captured the primary mechanical demands placed on the lower-limb joints. Nevertheless, a full three-dimensional investigation of similarly ecologically valid parkour landings should be considered for future work. In particular, female athletes have demonstrated differences in frontal-plane lower-limb mechanics and factors associated with ACL injury risk during landing tasks (Hewett et al., 2005; Leppänen et al., 2017). Therefore, future studies should also include female traceurs.

Finally, while this study marks the first attempt to assess drop landing mechanics in parkour according to the real loading placed upon traceurs it was still conducted in a controlled laboratory setting, which could not fully replicate the environmental variability and psychological demands of the real-world sport. Although the drop height and distance reflected typical parkour movements, factors such as uneven surfaces, novelty of the surroundings, and the psychological pressures

experienced were not represented (Elizondo-Donado et al., 2025; Pagnon et al., 2022), limiting ecological validity in this regard.

6. Conclusion

The present study investigated the joint mechanics of experienced traceurs performing two-metre drop landings under different verbal instructions. Its findings revealed that the habitual landing strategy effectively balances load management and energy absorption, while also exhibiting smaller inter-technique variability. Instructing traceurs to perform soft or stiff landings did not result in distinct advantages for joint load management or energy dissipation. Indeed, both of these instructions elicited alterations that may increase the risk of injury when compared to the athletes' habitual drop landing technique.

While the stiff instruction increased plantarflexor loading, its training value may be limited to lower heights where kinetic energy remains manageable. In contrast, the implementation of soft instructions did not prolong impact duration but rather reduced the traceurs capacity to actively dissipate energy. These findings emphasise the significance of preserving sport-specific movement strategies in contexts of extreme mechanical demand. Future research should explore the combined effects of external-only verbal cues, progressive landing heights and distinct landing conditions to better understand motor adaptability and reduce passive tissue stress. Despite its methodological limitations, this study provides novel insights into high-impact load management specific to parkour and offers valuable guidance for coaches. The habitual landing technique, refined through extensive practice, appears to be biomechanically favourable for managing the extreme physical demands of parkour. It is therefore recommended that caution be applied when modifying established patterns without robust evidence of its benefits.

CRedit authorship contribution statement

Kevin Soter: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Zanoni:** Writing – review & editing, Writing – original draft, Visualization, Software, Data curation. **Stephan Babel:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Disclosure statement

The authors report there are no competing interests to declare.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbmo.2026.100028>.

Data availability

Analysis script & reference data freely available on GitHub. Original data will be made available on request.

[IMPACT Analysis Script & Reference Data \(Reference data\) \(GitHub\)](#)

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