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Comparison of lightweight and traditional figure skating blades, a prototype blade with integrated damping system and a running shoe in simulated figure skating landings and vertical countermovement jumps, and evaluation of dampening properties of the prototype blade

Ondrej Spiegl, Olga Tarassova, Lina E. Lundgren, Daniel Neuman and Anton Arndt

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ABSTRACT
To date, there is no empirical evidence suggesting greater jump heights or cushioned landings when using figure skating (FS) blades of different mass and design. This study examined the effect of lightweight (Gold Seal Revolution from John Wilson) and traditional (Apex Supreme from Jackson Ultima and Volant from Riedell) blades, a new prototype blade with an integrated damping system (damping blade) in two different damping configurations, and running shoes (Runfalcon from Adidas) on kinetics and kinematics during simulated on-ice landings from 0.6 m and maximal countermovement jumps on synthetic ice, and measured dampening properties of the damping blade. Seventeen participants executed trials in the six footwear conditions blinded to the different blades and acted as their own control for statistical comparison. There were no differences between the lightweight and traditional blades on the maximal vertical ground reaction force during the landing. Image analysis showed a damping effect in the damping blade that significantly decreased the landing load for all participants (mean 4.38 ± 0.68 bodyweight) (p ≤ 0.006), on average between 10.1 and 14.3% compared to lightweight and traditional blades (4.87 ± 1.01 to 5.11 ± 0.88 bodyweight). The maximal jump height achieved was the same in all FS blades.

Introduction
The equipment used by figure skaters consists of figure skating (FS) boots and blades. These are traditionally selected based on discipline, skill level, ability and personal preferences by the skater, such as the stiffness of the boot and the blade profile, and in many cases on recommendations from coaches. Recent developments in FS equipment seem to have focused on reducing the mass of the equipment, which would be an advantage if it permitted skaters to achieve a greater jump height amongst other benefits.

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In terms of injury prevention, other sports develop well cushioned shoe and surface interfaces, which is recommended during high-impact energy activities (Chiu et al., 2001). However, existing FS boots and blades have rigid properties. In singles skating, chronic overuse injuries such as Achilles tendinopathy, patellar tendonitis, lower back pain and stress fractures are more common than acute injuries and are associated with the high loads absorbed during repeated landing impacts in the stiff figure skate (Bradley, 2006; Dubravcic-Simunjak et al., 2003; Dufek & Bates, 1991; Han et al., 2018; Jaworski & Ballantine-Talmadge, 2008; Lockwood et al., 1995; Porter et al., 2007; Porter, 2013). Therefore, modifying FS equipment to attenuate landing impacts may assist to reduce the risk of landing related overuse injuries.

The magnitude of the landing impact load (vertical ground reaction force (VGRF) expressed as body weight (BW)), that skaters experience is generally related to the jump height, the number of rotations in the air, the technique of execution and joint rotations (soft vs. stiff landing) which is also affected by the stiffness of the FS boots (Bradley, 2006; Bressel & Cronin, 2005; Lockwood & Gervais, 1997; Lockwood et al., 1995; Spiegl et al., 2019). For example, King et al. (1994) reported on-ice jump heights of 0.68 m, 0.65 m and 0.66 m for single, double and triple axel jumps respectively performed by elite male skaters. In an analysis of landing impacts in skates from a similar height of 0.5 m, with horizontal motion and a half vertical rotation in the air, an average VGRF of 5.0 BW was reported during laboratory landing trials on synthetic ice (Spiegl et al., 2019).

During countermovement jump take-off, Vaverka et al. (2016) reported 2.2 BW as an average VGRF of a 0.52 m high jump in regular running shoes. Furthermore, no differences were reported in the magnitude of the take-off VGRF in skates and barefoot, however the jump height was significantly reduced due to increased mass of the skates as well as to the limited plantar flexion permitted by the boot (Haguenauer et al., 2006).

FS blade manufacturers usually categorise different models of FS blades according to the FS discipline, performance level of the skater and complexity of jumps, i.e., for double jumps or triple jumps. Current models of FS blades differ in materials, weight, dimensions, blade profile, mechanical design, toe pick design and other features such as side honed edges and tapered blades. To date, no scientific research has been conducted to validate the functional benefit of different FS blade properties. Although blade manufacturers state greater jump height when using lightweight FS blades and cushioned landings in some FS blade models, such statements are scientifically unsupported and there are no studies that have confirmed the effects of different FS blades on kinetics and kinematics.

Existing FS blade models are rigid in construction while some ice hockey (Marsblade) and speed skating (klapskate) blade models are modified to allow some degree of pivotal or rocking movement of the blade-runner (the structure in contact with the ice) in the sagittal plane relative to the ice-skating boot and frame (the structure that mounts the blade-runner to the ice-skating boot), for a more natural movement pattern, which in klapskates enhanced the power output per stroke (Houdijk et al., 2000). A new type of FS blade with an integrated damping system (damping blade) was developed prior to this study to attenuate landing impacts from FS jumps. In the modified blade, the blade-runner can translate in the superior inferior and anterior posterior directions in the sagittal plane relative to the frame against elastic damping units that compress during the impact.
The purpose of this study was: (1) to evaluate kinetic and kinematic parameters using a prototype of the damping blade, lightweight and traditional FS blades and standard running shoes during figure skating landings and maximal vertical countermovement jumps (VCJ) with participants on artificial ice in order to compare different FS blades, and (2) to establish the dampening properties of the prototype damping blade by evaluating the displacement of the blade-runner relative to the frame with stiff and soft damping units using loads relevant to FS, and during the FS landing impact of a randomly selected landing trial of one participant. The null-hypothesis was that there are no differences in landing impact VGRF between the different FS blades (lightweight, traditional and damping blade) and running shoe conditions, and no differences in jump heights between the FS blade conditions.

**Method**

**Methodology for landing and maximal vertical countermovement jump trials with participants**

**Participants**

Seventeen active or recently retired male figure skaters (age 22 ± 7 years, mass: 69.5 ± 12.5 kg, height: 178.5 ± 11.5 cm) gave written consent to participate in the study. The inclusion criteria were to have consistent jumps of two rotations (720 degrees) on the ice, be injury-free and to fit skate size 41 (EUR). All participants preferred to rotate to the left side. The Swedish Ethical Review Authority approved the study (diary number: 2019–05955).

An a priori power analysis (G*Power v.3.1.9.3, Germany) was conducted to determine the sample size required to produce a power of 0.8 at an alpha level of 0.05, with an effect size of 0.4 (ANOVA, omnibus, one-way) or 0.8 (Paired Sample T-test), both indicating a large effect size (Cohen’s f). A sample size of at least 15 participants per group was required to achieve statistical power.

**Experimental protocol and data collection**

Participants executed landing and VCJ trials in five different FS blades and running shoes. The trials were executed on a force plate (Kistler type 9281EA, Kistler Instrumente AG, Winterthur, Switzerland: 2500 Hz), which was, together with the surrounding floor, covered with synthetic ice (four panels of area 10.44 m², Nordic Ice Consulting AB, Stockholm, Sweden), which allowed participants to glide away from the impact, thus simulating on-ice landings. The section covering the force plate was cut to the dimensions of the force plate with a 2 mm space to the surrounding sections to prevent dispersion of forces.

The landing trials were executed from a 0.6 m high box with the landing point situated 1 m from the box. Participants replicated a waltz jump by stepping away from the box with forward motion followed by a half vertical axis rotation (180 degrees) in the air and landing backwards on one leg as on the ice. In order to control the landing in the running shoes, the participants hopped away backwards from the landing point.

For the VCJ trials, the participants stood with their feet hip-width apart with their right foot on the force plate and the left foot outside. They performed maximal VCJ with arm swing.
All participants performed five trials of each task in six different footwear conditions in a randomised order. Apart from the running shoe condition, the participants were blinded to the different FS blades. The blades, mounted on FS boots, were covered with tape and the participants were reminded not to look at the blades throughout the trials. The participants reported not seeing the blades. Only one pair of FS boots was used throughout the study to standardise the conditions for the different blades. The participants kept the FS boots on while the blades were remounted between the trials. Some time was given to the participants to familiarise with the boots and blades by gliding, spinning and jumping on the synthetic ice before the start of the tests. The participants were asked to share their subjective experiences in the different FS blade conditions with the test leader.

During the trials, three-dimensional kinematics of the right lower extremity (as FS landings are performed on single leg) and trunk were investigated using a motion capture system (Oqus 4, Qualisys AB, Gothenburg, Sweden: twelve cameras, 250 Hz). Sixty-six passive reflective markers were placed on anatomical landmarks on the participant (Figure 1). Lower limb markers were placed bilaterally on the medial and lateral aspects of the knee, anterior superior iliac spine, greater trochanter and on the posterior superior iliac spine. Trunk markers were placed on the xiphoid process and on the seventh cervical vertebra. Upper limb markers were placed bilaterally on the acromioclavicular joint, lateral and medial epicondyle of humerus, radius-styloid process and ulna-styloid process and on the lateral and medial metacarpal head. Tracking clusters of four markers were placed on the anterior shank and thigh and clusters of three markers were placed on

Figure 1. Placement of the reflective markers.
the lateral arm and forearm. Six markers were placed on each FS boot and four on each running shoe, on the most anterior and posterior positions of the footwear, at the location of the first and fifth metatarsal heads, and for the FS boots at the location of the medial and lateral malleolus. In case of the running shoes, the markers were placed directly on the medial and lateral malleolus on the participants.

**Figure skates and running shoes**

Three conventional rigid FS blade models for high performance and novice categories were included: the lightweight Gold Seal Revolution (Gold Seal R) (John Wilson, HD Sports LTD, Sheffield, United Kingdom), the traditional Apex Supreme TB150 (Apex Supreme) (Jackson Ultima, Tournament Sports Marketing Inc., Cambridge, ON, Canada) and the traditional Eclipse Volant (Volant) (Riedell Shoe Inc. Red Wing, MN, USA). Furthermore, prototypes of the damping blade, with soft and stiff damping unit alternatives (damping blade\textsubscript{soft} and damping blade\textsubscript{stiff}) were included (Figure 2). The running shoe Runfalcon (Runfalcon) (Adidas GmbH, Herzogenaurath, Germany) in size 41 (EUR) was used as comparison to the skates. All the FS blades were of the same size (10.25”, for boot size 41) and mounted on Edea Concerto FS boots (Edea Skates srl, Crocetta del Montello, Italy) (size 275, corresponding to EUR size 41).

Before the tests, all FS blades were sharpened (Incredible Edger) to a radius of hollow (ROH) of 11 mm. As the same pair of blade-runners was used in damping blade\textsubscript{stiff} and damping blade\textsubscript{soft} conditions (i.e., twice per participant) this pair of blade-runners were resharpened half way through the study.

The FS blade characteristics differed slightly in materials, weight, dimensions, blade profile (radius of rocker, front lift and heel lift) and mechanical design. A general comparison between the footwear conditions is presented in Table 1 (explanation in Figure 3).

![Figure 2. FS blades and running shoe used in this study.](image-url)
Table 1. A general comparison between the FS blades and running shoes.

<table>
<thead>
<tr>
<th></th>
<th>Apex Supreme</th>
<th>Volant</th>
<th>Gold Seal R</th>
<th>Damping Bladestiff</th>
<th>Damping Bladesoft</th>
<th>Runfalcon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>400 †</td>
<td>325 †</td>
<td>256 †</td>
<td>314 (of which 45 are damping units) †</td>
<td>303 (of which 34 are damping units) †</td>
<td>240</td>
</tr>
<tr>
<td>Blade width (mm)</td>
<td>4</td>
<td>4</td>
<td>04-Mar</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Front height</td>
<td>52</td>
<td>44</td>
<td>47</td>
<td>54</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear height (mm)</td>
<td>55</td>
<td>46</td>
<td>50</td>
<td>57</td>
<td>57</td>
<td>-</td>
</tr>
<tr>
<td>Main radius (foot)</td>
<td>8'</td>
<td>7'</td>
<td>8'</td>
<td>8'</td>
<td>8'</td>
<td>-</td>
</tr>
<tr>
<td>Front lift (mm)</td>
<td>6.7</td>
<td>5.9</td>
<td>7.9</td>
<td>7.1</td>
<td>7.1</td>
<td>-</td>
</tr>
<tr>
<td>Heel lift (mm)</td>
<td>6.2</td>
<td>6.6</td>
<td>6.1</td>
<td>5.9</td>
<td>5.9</td>
<td>-</td>
</tr>
<tr>
<td>Materials</td>
<td>Carbon steel (the grade was not provided), titanium-based coating</td>
<td>Carbon steel (1075 AISI), chrome plating</td>
<td>Carbon steel (1075 AISI), chrome plating, carbon fibre frame</td>
<td>*</td>
<td>*</td>
<td>Mesh fabric, synthetic leather, ethyl vinyl acetate midsole</td>
</tr>
<tr>
<td>Intended purpose</td>
<td>Traditional FS blade, single to quadruple jumps</td>
<td>Traditional FS blade, single and double jumps</td>
<td>Lightweight FS blade, single to quadruple jumps</td>
<td>*</td>
<td>*</td>
<td>-</td>
</tr>
</tbody>
</table>

†The weight of the FS blade does not include the weight of the FS boot of 805 g (per boot).

*The damping blade prototype is described in more detail in a separate Section 2.2.
Data obtained from the motion capture system were collected and initially processed in the Qualisys Track Manager (QTM; Qualisys AB, Gothenburg, Sweden) and then analysed together with the force plate data in Visual3D v6 Professional software (C-Motion Inc. Germantown, MD, USA). The kinematic data were low-pass filtered using a digital fourth-order zero-lag Butterworth filter with a cut-off frequency of 7 Hz. The trunk angle was defined as the angle between the torso and the right thigh, the knee angle was defined between right shank and right thigh and the ankle angle between right foot and right shank (Figure 4). The flexion was defined as the rotation about the mediolateral (ML) axis. The force data were low-pass filtered using a digital fourth-order zero-lag Butterworth filter with a cut-off frequency of 350 Hz and then normalised to BW. Matlab (version R2020a, The Mathworks, Inc., Natick, MA, USA) was used to create curves representing mean force (BW) of all landings in each footwear condition for a visual representation, normalised to time (100% = 4 ms after the maximal VGRF).

Examples of the VGRF from the landing of a simulated waltz jump and the VCJ are shown in Figure 5. The kinetic landing variables analysed were: the first landing peak VGRF (LF\textsubscript{P1}), time from initial contact (IC) to the LF\textsubscript{P1} (TT-LF\textsubscript{P1}), the maximal VGRF
Figure 5. The vertical ground reaction force during landing from a waltz jump (a) and maximal VCJ take-off (b).

during landing (LF_max) and time from IC to the LF_max (TT-LF_max) (Figure 5(a)). The kinematic landing variables analysed were: right ankle, knee and trunk flexion at IC (LFLEX_IC), peak flexion (LFLEX_P), time from IC to LFLEX_P (TT-LFLEX_P) and the range of motion between IC and LFLEX_P (LROM).

The kinetic analysis of VCJ variables included the maximal VGRF during take-off (TF_MAX) and the time from minimal force during the unloading phase to the TF_MAX (TT-TF_MAX) (Figure 5(b)). The kinematic VCJ variables analysed were: the jump height (JUMP_H), peak flexion at the squat position before the take-off (TFLEX_PSQ), flexion at lift-off (TFLEX_LO), time from TFLEX_PSQ to TFLEX_LO (TT-TFLEX_LO) and the range of motion between TFLEX_PSQ and TFLEX_LO (LROM) of the right ankle, knee, and the trunk. JUMP_H was calculated as a difference between the position of the centre of mass (COM) during a jump and during a reference stand for the specific footwear condition.

Sixteen of 17 participants completed the trials in all footwear conditions. One participant did not complete the tests with the Gold Seal R condition due to lack of time and was therefore excluded from the statistical analysis. Due to difficulties in tracking motion data, kinematic data were not available for VCJ trials of one participant, and therefore VCJ variables were statistically analysed based on 15 participants. The data for the landing trials were complete and were therefore statistically analysed based on 16 participants.

Statistics
Participants acted as their own control for statistical comparison of dependent variables between the footwear conditions (average of five trials) using IBM SPSS Statistics software (version 26. Armonk, NY: IBM Corp.). Following testing for outliers, normal distribution (Shapiro–Wilks test) and sphericity (Mauchly’s test), either one-way repeated measures ANOVA type 3 or a non-parametric Friedman test were used to test for a main effect significance. When a main effect was present, either a post hoc pairwise comparison with Bonferroni correction or a Wilcoxon test of two related samples was used to test for significant differences between the specific footwear conditions. The level of significance was set at $p \leq 0.05$ for all statistical tests. The results compared with parametric statistics were expressed as mean ± standard deviation (SD) and with non-parametric statistics as median with interquartile range (IQR), including
the $p$-value and degrees of freedom ($\text{df}_{\text{factor}}, \text{df}_{\text{error}}$ for ANOVA and $\text{df}$ for Friedman test). $F$-values and effect size ($\eta^2$) are expressed for ANOVA and chi-squared distribution ($\chi^2$) for Friedman test.

Dampening properties of the prototype blade

The damping blade prototype was composed of a blade-runner made of 430 (AISI) stainless steel, a frame 3D printed with polyamide 12 (PA 12) (HP Multi Jet Fusion model 3200, HP 3D High Reusability PA 12, Hewlett-Packard, Palo Alto, CA, USA) and damping units 3D printed (HP Multi Jet Fusion model 5210) with thermoplastic polyurethane (TPU) 88 Shore A (BASF Ultrasint TPU01, BASF, Ludwigshafen, Germany) (Figure 6(a)). The stiffness of the damping units was intended to reduce the force during landing impacts, while not affecting the propulsive forces during jump take-offs. The soft alternatives of the damping units had a longitudinally extending cavity with a diameter of 13 mm (Figure 6(b)). The stiff alternatives included a 3D printed infill (FlashForge Dreamer, Zhejiang Flashforge 3D technology Co., LTD, Hangzhou, China) of TPU 93.
Shore A (Eco-TPU filament, Shenzhen Ecoreprap Technology Co. Ltd, Guangdong, China) in the cavity (Figure 6(b)). Compared to conventional rigid FS blades, the blade-runner of the damping blade model was not rigidly attached to the frame and the design allowed sliding movements of the blade-runner inside the frame against the damping units that compress under load during the landing impact. The permissible movement of the blade-runner was in the sagittal plane, in the superior inferior and anterior posterior directions relative to the frame with a maximal translation limited by the frame to 5 mm. As the frame covers a portion of the blade-runner from both sides in transversal axis relative to the blade runner, it prevents the blade-runner from longitudinal bending and twisting motion.

**Theoretical displacement range of the blade-runner**

To evaluate the theoretical range-of-displacement (TROD) of the blade-runner inside the damping blade assembly under loads a mechanical compression test (MTS Criterion C42.503, MTS Systems Corporation, Eden Prairie, MN, USA: 1000 Hz, one cycle of 1000 N, 1500 N, 2000 N, 2500 N, 3000 N, loading rate 8.3 mm/s) was conducted on the individual damping units (front and rear in soft and stiff alternatives). The test was conducted at room temperature and the damping units were subjected to preloading to remove the Mullins’ softening effect. Displacement (mm) was examined in relation to the applied force (N) and the force-displacement data were processed in Spike 2 v7.09a software (CED Inc. Milton, England). Fitted displacement curves and TROD of the blade-runner inside the damping blade assembly relative to the damping units were calculated and plotted using Matlab (version R2020a).

As two damping units were placed in the damping blade assembly, one in the front and second one in the rear section of the assembly (Figure 6(a,b)), the maximum displacement occurs when the full load is applied only to the rear damping unit and the lowest when the load is divided between the damping units (front and rear) in such a way that both deflect equally. The maximal and minimal displacement gave the total possible TROD. Minimal displacement for a given load was found from

\[ d(x)_{\text{rear}} = d(z)_{\text{front}} \]  

(1)

when the displacement \( d \) with respect to force \( x \) and \( z \) was equal between both damping units. A continuous displacement was found with a polynomial fit using the force-displacement data.

\[ p_1x^2 + p_2x + p_3 = q_1z^2 + q_2z + q_3 \]  

(2)

where the \( p_i \) and \( q_i \) are the fitting coefficients. Equation (2) simplified:

\[ (p_1x^2 - q_1z^2) + (p_2x - q_2z) + (p_3 - q_3) = 0 \]  

(3)

The average displacement was determined as an average of \( d_{\text{min}} \) and \( d_{\text{max}} \):

\[ \frac{d_{\text{max}} + d_{\text{min}}}{2} = \text{average displacement} \]  

(4)
**Blade-Runner displacement during landing impact**

One landing trial of one participant with the damping blade$_{\text{soft}}$ was randomly selected for evaluation of the degree of blade-holder shift in the frame in relation to the landing load. A compact video camera (Sony Cyber-Shot DSC-RX100M5A, Sony Corporation, Tokyo, Japan: 1000 fps) was positioned to capture the sagittal plane of the damping blade during the landing impact on the force plate. An image analysis of the captured images, occurring at LF$_{P1}$ and LF$_{\text{MAX}}$, using raster graphic images, resolution 1920 \times 1080 pixels and 300 DPI was processed in Adobe Illustrator (Adobe Inc., San Jose, CA, USA). Knowing the distance between two points in the plane (tip of the lower toe pick and the heel-end of the blade-runner, 305 mm) the scale of the image was determined (1 pixel = 0.22 mm) and the distance between the edges of the damping units and the frame was measured as the blade-runner shifted superiorly and superior-posteriorly. The accuracy due to image resolution was ±0.44 mm for superior-inferior and anterior-posterior measurements, and ±0.55 mm for diagonal superior-posterior measurement of 53 degrees angle (angle of measurements on the captured image) found from

\[
\alpha = \begin{cases} 
\frac{u}{\cos(\alpha)}, & \alpha \leq 45^\circ \\
\frac{u}{\sin(\alpha)}, & \alpha > 45^\circ 
\end{cases}
\]  

where \(u\) is the uncertainty 0.22 mm and \(\alpha\) is the angle of measurement. The direction of blade-runner shift was evaluated relative to local coordinate system of the damping blade.

**Results**

**Landing trials**

LF$_{P1}$ was significantly lower for the damping blade$_{\text{soft}}$ (median of 1.34 (0.43) BW) and damping blade$_{\text{stiff}}$ (1.44 (0.41) BW) compared to conventional rigid FS blade (Gold Seal R, Apex Supreme and Volant) and the running shoe conditions, which had a median range of 1.87 (0.38) to 2.14 (0.47) BW, \((p < 0.001)\) (Table 2). The Apex Supreme had significantly higher LF$_{P1}$ (2.14 (0.47) BW) compared to the Gold Seal R (1.87 (0.38) BW) and Volant (1.92 (0.28) BW) FS blades \((p \leq 0.015)\). No significant difference in the LF$_{\text{MAX}}$ was observed between the lightweight and traditional FS blades (Gold Seal R, Apex Supreme and Volant); however, significant differences were present for the prototype damping blade (Table 2 and Figure 7). LF$_{\text{MAX}}$ was significantly lower for the damping blade$_{\text{soft}}$ (mean of 4.38 ± 0.68 BW) compared to conventional rigid FS blade and the damping blade$_{\text{stiff}}$ conditions, which had a mean range of 4.8 ± 0.95 to 5.11 ± 0.88 BW, \((p \leq 0.018)\). The damping blade$_{\text{stiff}}$ (4.8 ± 0.95 BW) was significantly lower compared to the Apex Supreme (5.11 ± 0.88 BW) \((p = 0.03)\). The LF$_{P1}$ decreased on average between 27.7–37.1% in damping blade$_{\text{soft}}$ and 22.6–32.6% in damping blade$_{\text{stiff}}$, and the LF$_{\text{MAX}}$ decreased between 10.1% and 14.3% in damping blade$_{\text{soft}}$ compared to the conventional rigid FS blade conditions.
Table 2. Comparison of landing variables between the Apex Supreme (A), Volant (V), Gold Seal R (G), Damping Blade<sub>stiff</sub> (St), Damping Blade<sub>soft</sub> (So) and Runfalcon (R), the values are expressed as mean ± SD or median (IQR). Significant differences between specific means or medians are indicated with abbreviation representing significantly lower mean or median in comparison to the specific footwear condition. Significantly lowest mean or median values in comparison to all the other footwear conditions are marked with an asterisk (*).

<table>
<thead>
<tr>
<th></th>
<th>Apex Supreme (A)</th>
<th>Volant (V)</th>
<th>Gold Seal R (G)</th>
<th>Damping Blade&lt;sub&gt;stiff&lt;/sub&gt; (St)</th>
<th>Damping Blade&lt;sub&gt;soft&lt;/sub&gt; (So)</th>
<th>Runfalcon (R)</th>
<th>p-value</th>
<th>F</th>
<th>np²</th>
<th>χ²</th>
<th>df</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF&lt;sub&gt;P1&lt;/sub&gt;(BW)</td>
<td>2.14 (0.47)</td>
<td>1.92 (0.28)&lt;sup&gt;A&lt;/sup&gt;</td>
<td>1.87 (0.38)&lt;sup&gt;A&lt;/sup&gt;</td>
<td>1.44 (0.41)&lt;sup&gt;A&lt;/sup&gt;, G, R</td>
<td>1.34 (0.43)&lt;sup&gt;A&lt;/sup&gt;</td>
<td>1.92 (0.58)</td>
<td>&lt;0.001</td>
<td>-</td>
<td>-</td>
<td>55.71</td>
<td>5</td>
</tr>
<tr>
<td>TT-LF&lt;sub&gt;P1&lt;/sub&gt; (s)</td>
<td>0.002 ± 0.001&lt;sup&gt;St&lt;/sup&gt; So, R</td>
<td>0.003 ± 0.001&lt;sup&gt;St&lt;/sup&gt; So, R</td>
<td>0.003 ± 0.002&lt;sup&gt;St&lt;/sup&gt; So, R</td>
<td>0.005 ± 0.003&lt;sup&gt;St&lt;/sup&gt; So, R</td>
<td>0.007 ± 0.003&lt;sup&gt;R&lt;/sup&gt;</td>
<td>0.018 ± 0.003</td>
<td>&lt;0.001</td>
<td>190.89</td>
<td>0.93</td>
<td>(3,38)</td>
<td></td>
</tr>
<tr>
<td>LF&lt;sub&gt;MAX&lt;/sub&gt; (BW)</td>
<td>5.11 ± 0.88</td>
<td>5.05 ± 1.01</td>
<td>4.87 ± 1.01</td>
<td>4.8 ± 0.95&lt;sup&gt;A&lt;/sup&gt;</td>
<td>4.38 ± 0.68&lt;sup&gt;A&lt;/sup&gt;, V, G, St</td>
<td>4.7 ± 0.58</td>
<td>0.003</td>
<td>6.73</td>
<td>0.31</td>
<td>(2,24)</td>
<td></td>
</tr>
<tr>
<td>TT-LF&lt;sub&gt;MAX&lt;/sub&gt;(s)</td>
<td>0.046 (0.014)&lt;sup&gt;R&lt;/sup&gt;</td>
<td>0.046 (0.013)&lt;sup&gt;R&lt;/sup&gt;</td>
<td>0.049 (0.014)&lt;sup&gt;R&lt;/sup&gt;</td>
<td>0.046 (0.015)&lt;sup&gt;R&lt;/sup&gt;</td>
<td>0.05 (0.015)&lt;sup&gt;R&lt;/sup&gt;</td>
<td>0.064 (0.015)</td>
<td>&lt;0.001</td>
<td>-</td>
<td>-</td>
<td>56.43</td>
<td>5</td>
</tr>
<tr>
<td>LFLEX&lt;sub&gt;C&lt;/sub&gt; foot (°)</td>
<td>146.98 ± 3.73</td>
<td>147.05 ± 3.94</td>
<td>146.73 ± 3.62</td>
<td>147.64 ± 4.23</td>
<td>147.44 ± 4.16</td>
<td>147.74 ± 5.29</td>
<td>&gt;0.05</td>
<td>8.01</td>
<td>0.33</td>
<td>-13,175</td>
<td></td>
</tr>
<tr>
<td>LFLEX&lt;sub&gt;C&lt;/sub&gt; knee (°)</td>
<td>153.77 ± 2.81</td>
<td>153.65 ± 2.67</td>
<td>154.52 ± 2.83</td>
<td>154.23 ± 2.72</td>
<td>154.05 ± 2.93</td>
<td>155.55 ± 4.33</td>
<td>&gt;0.05</td>
<td>3.38</td>
<td>0.18</td>
<td>(2,33)</td>
<td></td>
</tr>
<tr>
<td>LFLEX&lt;sub&gt;C&lt;/sub&gt; trunk (°)</td>
<td>150.22 ± 5.5</td>
<td>150.73 ± 5.71</td>
<td>151.01 ± 5.92</td>
<td>150.35 ± 6.04</td>
<td>150.29 ± 5.81</td>
<td>150.14 ± 5.72</td>
<td>&gt;0.05</td>
<td>0.6</td>
<td>0.04</td>
<td>(5,75)</td>
<td></td>
</tr>
<tr>
<td>LFLEX&lt;sub&gt;P&lt;/sub&gt; foot (°)</td>
<td>106.45 ± 4.09</td>
<td>105.76 ± 3.58</td>
<td>106.49 ± 3.6</td>
<td>107.36 ± 3.24</td>
<td>107.26 ± 2.93</td>
<td>91.22 ± 3.53&lt;sup&gt;*&lt;/sup&gt;</td>
<td>&lt;0.001</td>
<td>248</td>
<td>0.94</td>
<td>(3,40)</td>
<td></td>
</tr>
<tr>
<td>LFLEX&lt;sub&gt;P&lt;/sub&gt; knee (°)</td>
<td>110.44 ± 6.62</td>
<td>110.44 ± 5.85</td>
<td>111.71 ± 6.06</td>
<td>111.33 ± 5.95</td>
<td>110.4 ± 5.68</td>
<td>113.27 ± 4.78</td>
<td>&gt;0.05</td>
<td>2.89</td>
<td>0.16</td>
<td>(3,42)</td>
<td></td>
</tr>
<tr>
<td>LFLEX&lt;sub&gt;P&lt;/sub&gt; trunk (°)</td>
<td>102.34 ± 11.42&lt;sup&gt;R&lt;/sup&gt;</td>
<td>104.55 ± 9.47&lt;sup&gt;R&lt;/sup&gt;</td>
<td>104.79 ± 11.16&lt;sup&gt;R&lt;/sup&gt;</td>
<td>102.4 ± 10.25&lt;sup&gt;R&lt;/sup&gt;</td>
<td>102.44 ± 10.14&lt;sup&gt;R&lt;/sup&gt;</td>
<td>111.74 ± 7.43</td>
<td>&lt;0.001</td>
<td>12.22</td>
<td>0.45</td>
<td>(5,75)</td>
<td></td>
</tr>
<tr>
<td>TT-LFLEX&lt;sub&gt;P&lt;/sub&gt; foot (s)</td>
<td>0.12 (0.04)&lt;sup&gt;St&lt;/sup&gt;</td>
<td>0.12 (0.02)</td>
<td>0.12 (0.03)</td>
<td>0.13 (0.05)</td>
<td>0.12 (0.04)</td>
<td>0.11 (0.02)&lt;sup&gt;G&lt;/sup&gt;, St So</td>
<td>0.037</td>
<td>-</td>
<td>-</td>
<td>11.82</td>
<td>5</td>
</tr>
<tr>
<td>TT-LFLEX&lt;sub&gt;P&lt;/sub&gt; knee (s)</td>
<td>0.19 (0.06)</td>
<td>0.19 (0.07)</td>
<td>0.18 (0.09)</td>
<td>0.18 (0.08)</td>
<td>0.19 (0.07)</td>
<td>0.16 (0.03)&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.019</td>
<td>-</td>
<td>-</td>
<td>13.48</td>
<td>5</td>
</tr>
<tr>
<td>TT-LFLEX&lt;sub&gt;P&lt;/sub&gt; trunk (s)</td>
<td>0.32 ± 0.05</td>
<td>0.31 ± 0.04</td>
<td>0.32 ± 0.06</td>
<td>0.33 ± 0.03</td>
<td>0.32 ± 0.04</td>
<td>0.23 ± 0.03&lt;sup&gt;*&lt;/sup&gt;</td>
<td>&lt;0.001</td>
<td>18.67</td>
<td>0.55</td>
<td>(5,75)</td>
<td></td>
</tr>
<tr>
<td>L&lt;sub&gt;ROM&lt;/sub&gt; foot (°)</td>
<td>40.53 ± 4.92&lt;sup&gt;R&lt;/sup&gt;</td>
<td>41.29 ± 5.03&lt;sup&gt;R&lt;/sup&gt;</td>
<td>40.23 ± 4.76&lt;sup&gt;R&lt;/sup&gt;</td>
<td>40.27 ± 4.39&lt;sup&gt;R&lt;/sup&gt;</td>
<td>40.18 ± 4.31&lt;sup&gt;R&lt;/sup&gt;</td>
<td>56.52 ± 6.87</td>
<td>&lt;0.001</td>
<td>129.67</td>
<td>0.89</td>
<td>(2,29)</td>
<td></td>
</tr>
<tr>
<td>L&lt;sub&gt;ROM&lt;/sub&gt; knee (°)</td>
<td>42.21 (5.56)</td>
<td>42.46 (4.31)</td>
<td>41.46 (5.73)</td>
<td>41.04 (4.11)</td>
<td>41.58 (5.52)</td>
<td>42.75 (7.69)</td>
<td>&gt;0.05</td>
<td>-</td>
<td>-</td>
<td>2.53</td>
<td>5</td>
</tr>
<tr>
<td>L&lt;sub&gt;ROM&lt;/sub&gt; trunk (°)</td>
<td>47.88 ± 9.44</td>
<td>46.18 ± 7.57</td>
<td>46.22 ± 9.43</td>
<td>47.95 ± 7.62</td>
<td>47.85 ± 8.26</td>
<td>38.40 ± 5.54&lt;sup&gt;*&lt;/sup&gt;</td>
<td>&lt;0.001</td>
<td>13.89</td>
<td>0.48</td>
<td>(3,40)</td>
<td></td>
</tr>
</tbody>
</table>
A significant main effect between the footwear conditions was not present for the VCJ kinetic variables $TF_{\text{MAX}}$ and $TT-TF_{\text{MAX}}$ (Table 3). There were no significant differences in the $\text{JUMP}_H$ between the FS blade conditions with a mean range from 0.39 ± 0.06 to 0.4 ± 0.06 m, however, a significantly greater $\text{JUMP}_H$ ($p < 0.001$) was observed in the Runfalcon running shoe condition (0.51 ± 0.08 m) which was more than 1642 g lighter than the FS boots with blades (per pair) and in which participants achieved greater dorsiflexion of the feet during the countermovement ($p < 0.001$), greater extension of the knees at lift-off ($p < 0.001$) and utilised greater $T_{\text{ROM}}$ of the feet, knees and trunk ($p < 0.001$).

**Feedback on different FS blade conditions**

After the landing trials, 5 of the 17 participants reported softer landings in the damping blade$_{\text{soft}}$, compared to other FS blade conditions and the rest reported no differences. During the VCJ, 14 of the 17 participants reported perceiving the distance between the first toe pick and the ice surface (front lift), to be the shortest in the Volant FS blades, which was correctly reported, however did not affect the VCJ kinematics. The participants did not report feeling any difference in the jump height across the FS blade conditions. Although the same pair of blade-runners was used in the damping blade$_{\text{soft}}$ and damping blade$_{\text{stiff}}$ configurations, nine of the seventeen participants reported feeling a difference in the sharpness of the edges and blade profile.
Table 3. Comparison of VCJ variables between the Apex Supreme (A), Volant (V), Gold Seal R (G), Damping Blade stiff (St), Damping Blade soft (So) and Runfalcon (R). The values are expressed as mean ± SD. Significant differences between specific means are indicated with abbreviation representing significantly lower mean in comparison to the specific footwear condition. Significantly lowest mean values in comparison to all the other footwear conditions are marked with an asterisk (*).

<table>
<thead>
<tr>
<th></th>
<th>Apex Supreme (A)</th>
<th>Volant (V)</th>
<th>Gold Seal R (G)</th>
<th>Damping Bladestiff (St)</th>
<th>Damping Bladesoft (So)</th>
<th>Runfalcon (R)</th>
<th>p-value</th>
<th>Fnp² df</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF MAX (BW)</td>
<td>1.41 ± 0.16</td>
<td>1.41 ± 0.15</td>
<td>1.41 ± 0.16</td>
<td>1.4 ± 0.16</td>
<td>1.4 ± 0.15</td>
<td>1.38 ± 0.2</td>
<td>&gt;0.05</td>
<td>0.75</td>
</tr>
<tr>
<td>TT-TF MAX (s)</td>
<td>0.52 ± 0.15</td>
<td>0.52 ± 0.15</td>
<td>0.51 ± 0.16</td>
<td>0.52 ± 0.17</td>
<td>0.52 ± 0.14</td>
<td>0.49 ± 0.12</td>
<td>&gt;0.05</td>
<td>0.55</td>
</tr>
<tr>
<td>JUMP (m)</td>
<td>0.39 ± 0.07 R</td>
<td>0.4 ± 0.06 R</td>
<td>0.39 ± 0.07 R</td>
<td>0.39 ± 0.07 R</td>
<td>0.39 ± 0.06 R</td>
<td>0.51 ± 0.08</td>
<td>&lt;0.001</td>
<td>80.6</td>
</tr>
<tr>
<td>TFLEX PSQ foot (°)</td>
<td>108.24 ± 5.35</td>
<td>106.02 ± 4.5</td>
<td>5</td>
<td>106.91 ± 4.96</td>
<td>107.29 ± 4.89</td>
<td>89.57 ± 5.7°</td>
<td>&lt;0.001</td>
<td>170.6</td>
</tr>
<tr>
<td>TFLEX PSQ knee (°)</td>
<td>87.24 ± 10.38</td>
<td>86.67 ± 9.03</td>
<td>88.49 ± 9.89</td>
<td>86.68 ± 10.31</td>
<td>86.82 ± 9.94</td>
<td>84.17 ± 12.09</td>
<td>&gt;0.05</td>
<td>3.49</td>
</tr>
<tr>
<td>TFLEX PSQ trunk (°)</td>
<td>76.09 ± 10.23 R</td>
<td>77.33 ± 9.92</td>
<td>78.68 ± 10.48</td>
<td>77.42 ± 10.76</td>
<td>78.13 ± 9.82</td>
<td>73.49 ± 13.1</td>
<td>&lt;0.001</td>
<td>5.89</td>
</tr>
<tr>
<td>TFLEX CO foot (°)</td>
<td>147.55 ± 2.94</td>
<td>146.44 ± 2.56</td>
<td>147.5 ± 2.72</td>
<td>147.82 ± 3.13</td>
<td>148.2 ± 3.19</td>
<td>147.94 ± 4.92</td>
<td>&gt;0.05</td>
<td>1.71</td>
</tr>
<tr>
<td>TFLEX CO knee (°)</td>
<td>155.26 ± 3.13</td>
<td>155.09 ± 3.22</td>
<td>155.66 ± 2.86</td>
<td>155.34 ± 2.74</td>
<td>155.26 ± 3</td>
<td>158.65 ± 2.6</td>
<td>&lt;0.001</td>
<td>11.63</td>
</tr>
<tr>
<td>TFLEX CO trunk (°)</td>
<td>142.03 ± 6.17 R</td>
<td>143.35 ± 5.61</td>
<td>143.33 ± 6.18 R</td>
<td>142.91 ± 6.16 R</td>
<td>144.07 ± 6.11</td>
<td>146.95 ± 5.01</td>
<td>&lt;0.001</td>
<td>6.6</td>
</tr>
<tr>
<td>TT-TFLEX CO foot (s)</td>
<td>0.25 ± 0.09</td>
<td>0.24 ± 0.07</td>
<td>0.24 ± 0.08</td>
<td>0.25 ± 0.08</td>
<td>0.24 ± 0.08</td>
<td>0.26 ± 0.08</td>
<td>&gt;0.05</td>
<td>0.57</td>
</tr>
<tr>
<td>TT-TFLEX CO knee (s)</td>
<td>0.25 ± 0.07</td>
<td>0.25 ± 0.06</td>
<td>0.24 ± 0.08</td>
<td>0.25 ± 0.06</td>
<td>0.25 ± 0.07</td>
<td>0.25 ± 0.07</td>
<td>&gt;0.05</td>
<td>0.71</td>
</tr>
<tr>
<td>TT-TFLEX CO trunk (s)</td>
<td>0.29 ± 0.04</td>
<td>0.3 ± 0.03</td>
<td>0.29 ± 0.04</td>
<td>0.3 ± 0.04</td>
<td>0.3 ± 0.04</td>
<td>0.3 ± 0.04</td>
<td>&gt;0.05</td>
<td>0.49</td>
</tr>
<tr>
<td>TRROM foot (°)</td>
<td>39.32 ± 4.22 R</td>
<td>40.42 ± 4.16 R</td>
<td>41.36 ± 4.69 R</td>
<td>40.91 ± 4.08 R</td>
<td>40.92 ± 5.23 R</td>
<td>58.36 ± 7.27</td>
<td>&lt;0.001</td>
<td>97.48</td>
</tr>
<tr>
<td>TRROM knee (°)</td>
<td>68.02 ± 10.42 R</td>
<td>68.42 ± 9.3 R</td>
<td>67.17 ± 10.34 R</td>
<td>68.66 ± 9.7 R</td>
<td>68.43 ± 10.31 R</td>
<td>74.47 ± 12.26</td>
<td>&lt;0.001</td>
<td>11.02</td>
</tr>
<tr>
<td>TRROM trunk (°)</td>
<td>65.94 ± 10.6 R</td>
<td>67.02 ± 8.89 R</td>
<td>64.65 ± 11.07 R</td>
<td>65.5 ± 9.5 R</td>
<td>65.94 ± 9.6 R</td>
<td>73.46 ± 11.98</td>
<td>&lt;0.001</td>
<td>16.54</td>
</tr>
</tbody>
</table>
Dampening properties of the prototype damping blade

During mechanical compression tests the soft front and rear alternatives of damping units compressed to a greater extent (6.4 mm and 7 mm, respectively) compared to the stiff front and rear alternatives (4 mm and 5 mm, respectively) under the load of 3000 N (Figure 8(a)).

The TROD of the blade-runner supported by the stiff front and rear damping unit alternatives would be $1.0 \pm 0.4$ mm at 1000 N (approximately representing take-off load) and $3.5 \pm 1.4$ mm at 3000 N (approximately representing landing load) (Figure 8(b)). Using the soft front and rear alternatives, the displacement would range between $1.1 \pm 0.4$ mm at 1000 N and $4.8 \pm 2.4$ mm at 3000 N (Figure 8(c)).

**Figure 8.** Fitted displacement curves of individual damping units in the soft and stiff alternatives (a), TROD of the blade-runner in the frame with stiff damping units (b), and TROD of the blade-runner in the frame with soft damping units (c).
During the randomly selected landing trial of one participant, the damping units in the damping blade, compressed under the load and the blade-runner shifted superiorly and posteriorly relative to the anteroposterior axis of the frame (Figure 9(a–c)). During the IC, only the front damping unit compressed and the blade-runner shifted superior-posteriorly at an acute angle, 1.8 ± 0.55 mm under the load of 983 N (LF\textsubscript{P1}) (Figure 9(b)). Both damping units compressed during the full contact of the blade-runner with the ice.
and the blade-runner shifted superiorly, 2.4 ± 0.44 mm in the front and 3.5 ± 0.44 mm in the rear section of the assembly under the load of 2485 N (LF\textsubscript{MAX}) (Figure 9(c)). As a reference, a mechanical compression test of the soft rear damping unit using similar load is presented in Figure 9(d,e).

**Discussion and implications**

The current research aimed to examine whether different models of FS blades, conventional rigid (lightweight Gold Seal R, and traditional Apex Supreme and Volant) and a new damping blade prototype with soft and stiff damping unit alternatives, affected the kinetic and kinematic properties of the landings from FS jump and VCJ, with running shoes Runfalcon being used as a reference. The results showed significant differences between the damping blade and conventional rigid FS blade conditions for the landing variables LF\textsubscript{P1}, TT-LF\textsubscript{P1} and LF\textsubscript{MAX} (p ≤ 0.003) (Table 2) and no significant effect between the FS blade conditions for the VCJ variables TF\textsubscript{MAX}, TT-TF\textsubscript{MAX} and JUMP\textsubscript{H} (p > 0.05) (Table 3). Greater JUMP\textsubscript{H} was, however, observed in the Runfalcon running shoes compared to FS blade conditions (p < 0.001). The image analysis of the damping blade\textsubscript{soft} during the landing trial verified the damping effect. The research hypothesis was partially rejected as there were significant differences between the footwear conditions in the VGRF during landing impacts.

The Apex Supreme had the highest average LF\textsubscript{P1} and LF\textsubscript{MAX} of all tested footwear conditions (Table 2 and Figure 7). The lowest LF\textsubscript{P1} and LF\textsubscript{MAX} occurred in the damping blade\textsubscript{soft} compared to conventional rigid FS blade conditions (p ≤ 0.006) as well as compared to the damping blade\textsubscript{stiff} (p ≤ 0.018). As there were no differences between the damping blade\textsubscript{soft} and conventional rigid FS blade conditions in the landing kinematics (LF\textsubscript{LEXIC}, LF\textsubscript{LEXP} and L\textsubscript{ROM} of the foot, knee and trunk, and timing of joint flexion), it seems that the damping effect caused the reduced LF\textsubscript{P1} and LF\textsubscript{MAX} in the damping blade\textsubscript{soft} (Figure 9). The blade-runner in the damping blade prototype can slide inside the frame superiorly and posteriorly (Figure 9(b,c)); therefore, it dynamically interacts with the direction and location of the ground reaction force vector. This would explain why the damping blade prototype affects both peaks, the LF\textsubscript{P1} and LF\textsubscript{MAX}. The landing impact load during the full contact (Figure 9(c)) was distributed between the two damping units in the assembly and the blade-runner shift (2.4 ± 0.44 mm in the front and 3.5 ± 0.44 mm in the rear) was close to the calculated average TROD (3.6 mm) for the same load (Figure 8(c)), despite the mechanical compression tests being conducted at a lower loading rate (3000 N in 0.5 s compared to 3000 N in 0.05 s). The elastic material of the damping units absorbs some of the force by deforming during the landing impact, reducing the acceleration and total momentum transferred to the FS boot (Avanzini & Gallina, 2011; Daneshvar et al., 2011; Gawlak et al., 2017; Li & Darby, 2006; Luo et al., 2017; Reggio and De Angelis, 2014). As repeated landing impacts in FS are associated with several common chronic overuse injuries (Bradley, 2006; Han et al., 2018; Porter et al., 2007), using the damping system in FS landings presents a potentially important innovation in FS equipment with emphasis on injury prevention.

The observed differences in the landing impact VGRF (LF\textsubscript{P1} and LF\textsubscript{MAX}) between the damping blade\textsubscript{soft} and the damping blade\textsubscript{stiff} suggest that the stiffness of the damping units and the compression range (the load-displacement curve) are essential factors that
determine the effectiveness to dissipate the impact force (Baltich et al., 2015; Kulmala et al., 2018; Luo et al., 2017; Maropoulos et al., 2017; Ucar & Basdogan, 2018; Yu et al., 2019). Based on the TROD calculation, the blade-runner, supported by the soft damping units, would displace in the frame of the damping blade in the range of 4.4 ± 2.2 mm during a load of 2866 N (average $L_{\text{MAX}}$ of the damping blade$_{\text{soft}}$), while using the stiff alternatives the blade-runner would displace in the range of 3.6 ± 1.5 mm during a load of 3129 N, (average $L_{\text{MAX}}$ of the damping blade$_{\text{stiff}}$).

In general, the magnitude of the VGRF during the landing impact is dependent on the individual landing strategy (Yeow et al., 2011; Zhang et al., 2000) and body weight. The influence of landing strategy was evident in this study, as a participant weighing 82 kg utilised greater $L_{\text{ROM}}$ of foot and trunk during the landing, and was exposed to similar absolute maximal load during the landing impact as a participant weighing 57 kg: 3110 N and 3080 N respectively. Therefore, the stiffness of shock-absorbing components used in FS equipment to reduce the landing impact load can only be partially linked to the weight of the skater.

If shock-absorbing components are to be integrated into FS blades or boots, the stiffness must be sufficient not to compromise the propulsive forces during the take-off, as described in LaPorta et al. (2013) and Stefanyshyn and Nigg (2000) who examined effects of footwear on vertical jump. Although both $T_{\text{FMAX}}$ during the VCJ (Table 3) and $L_{F1}$ during the landing (Table 2) were of similar magnitudes, the $L_{F1}$ was significantly reduced in the damping blade compared to other footwear conditions while the $T_{\text{FMAX}}$ was unaffected. As the peaks of $T_{\text{FMAX}}$ and $L_{F1}$ occurred at different rates, 0.52 s during the take-off (TT-$T_{\text{FMAX}}$) and 0.007 s during the landing (TT-$L_{F1}$) in the damping blade$_{\text{soft}}$, this suggests a greater effect of damping on impacts with increased loading rate, as described in Boyer and Nigg (2004). Based on TROD calculation, the blade-runner supported by the soft or stiff alternatives of damping units would displace in the frame of the damping blade in the range of 0.9 ± 0.4 mm under a load of around 900 N corresponding to $T_{\text{FMAX}}$ in this study. However, the damping units in the damping blade conditions did not affect the kinetics and kinematics of VCJ in this study. This suggests suitable stiffness of the damping units both for landings and take-offs, at least for skaters of mass 69.5 ± 12.5 kg performing tasks of similar loads. Softer damping units may be relevant for skaters of lower weight than those who participated in this study. Since the stiffness, displacement capability and construction approach of the damping system are essential variables (Agualnado & Mahar, 2003; Ucar & Basdogan, 2018), any damping system used in FS equipment should be tested to determine the ability to dissipate the VGRF at landing impact without affecting the take-off.

The lack of significant differences between the conventional rigid FS blades suggests that the material, weight, mechanical design and blade profile of the different lightweight and traditional rigid blades in current use do not affect the maximal VGRF during landing and VCJ take-off as well as the jump height. This has practical implications for coaches, as they usually recommend equipment to their skaters. The conventional rigid FS blades act as rigid bodies, resulting in high peak VGRF during impact. Although the same steel is used in the Volant and Gold Seal R blades, the Gold Seal R also incorporates a carbon fibre frame intended to reduce the mass and improve cushioning. However, no extra shock-absorbing effect could be seen in this study.
The average jump height in skates reported by Haguenauer et al. (2006) was lower (0.27 m) compared to in this study (0.39 m), however the jump in Haguenauer et al. (2006) study was static without arm swing compared to counter-movement jump with stretch-shortening cycle and arm swing in this study. Although no significant differences were observed between the FS blade conditions alone, the stiffness of the skates, which limits the range of motion of the feet and knees, and the increased mass decreased the JUMP$_{H}$ compared to the running shoes. Blade manufacturers ordinarily claim greater jump heights when using lightweight FS blades, however, the mass difference of 44% (288 g) between the lightweight Gold Seal R and the traditional Apex Supreme blades did not affect the JUMP$_{H}$ in this study.

Landing and VCJ trials with expert participants were conducted in this study as mechanical testing alone cannot simulate individual technique and characteristics of different skaters when evaluating the performance of FS blades. The tests were conducted in a laboratory setting where the floor surface and the force plate were covered with synthetic ice, which facilitated controlled conditions for the landing and VCJ trials. The waltz jump performed in this study has only half a rotation, so the time to kinematically absorb VGRF during the landing phase is longer and the impact can be minimised (Lockwood et al., 1995). The waltz jump was selected due to being easy to control and safe to execute in laboratory conditions on synthetic ice as opposed to multiple revolution jumps. As multi revolution jumps showed increased impact during landing (Lockwood & Gervais, 1997), stiffer damping units may therefore be relevant to skaters of elite level.

Although the VCJ is a well-established and valid test for figure skaters, the take-off executed during FS performance is different compared to the VCJ take-off in this study. Depending on the type of FS jump, the take-off is often executed from one leg which may increase the load on the FS blade. Furthermore, on the ice, skaters also utilise the horizontal speed from glide entrance as well as the momentum of the arm swing and the free leg to increase the jump height (King, 2001). Due to these sport specific tasks, further studies are recommended to compare the different FS blades during FS performance.

There are some methodological considerations to take into account, although we judge that these factors had limited effect on the results. The blade-runners of the damping blade made of stainless steel 430 (AISI) and the Apex Supreme (the steel grade was not provided) were getting slightly dull towards the end of the study. The stainless steel 430 used in the damping blade prototype is not optimal for FS blades due to poor sharp edge retention, however it was chosen due to low prototyping cost. The skaters performed the trials with an in-shoe pressure measuring system (Pedar-X, Novel GmbH, Munich, Germany), with Pedar-X box, Novel wireless unit and battery attached by a belt to the participant’s hip. The in-shoe pressure data are part of a larger study and were not included in the current analysis.

**Conclusions**

The damping units included in the damping blade$_{soft}$ significantly decreased the maximal impact VGRF during landing for all participants on average between 10.1% and 14.3% compared to the conventional rigid FS blades, without affecting the landing kinematics or
the kinetics and kinematics of VCJ. This suggests suitable stiffness of the damping units for skaters of mass 69.5 ± 12.5 kg performing tasks of similar loads. No differences in maximal VGRF during the landing and VCJ take-off were seen between the Gold Seal R, Apex Supreme and Volant FS blades. The maximal jump height achieved in VCJ trials was the same for all FS blade conditions, despite the damping units included in the damping blade prototype and a 44% mass difference between the lightweight and traditional FS blades.

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Disclosure statement

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