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MTPJ Motion and Lower Limb Loadings during Ballet Jump Landings

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Abstract

Introduction: Overuse injuries are an issue within ballet dance, where plantar fasciitis is one. However, research of the biomechanical risk factors, which can cause plantar fasciitis during ballet jump landings, is sparse. Therefore, the aim of the present study is to 1) investigate the MTPJ motion and lower limb loadings during different ballet jump landings and 2) suggest alternative implementations during ballet jump landings to prevent the occurrence of plantar fasciitis.

Methods: Four ballet dancers participated in the present study. The dancers performed multiple Sautés in First Position, Relevés Sur le Cou-de-Pied Derriere, Grand Jeté, and Grand Pas de Chat jump landings on a force platform. The participants wore foot thongs, while a three-segment kinematic model of the foot and shank was used to provide a more detailed understanding of the metatarsophalangeal joint (MTPJ) and ankle joint postures during landings.

Results: The results indicate high vertical ground reaction force (vGRF) peaks during the Grand Jeté and Grand Pas de Chat landings. The highest negative ankle power peaks are registered during the Grand Pas de Chat landings, while the Grand Jeté landings illustrate larger MTPJ dorsiflexion angle at vGRF peak compared with the Grand Pas de Chat landings. Furthermore, Participant 2 demonstrates much higher MTPJ angles and MTPJ negative angular velocities at vGRF peaks during the Grand Jeté and Grand Pas de Chat landings compared with Participant 1.

Conclusion: Sprung floors, additional shoe cushioning, and eccentric muscle training programs may reduce the ankle joint and MTPJ loadings during ballet jump landings, and thereby reduce the risk for developing plantar fasciitis.

Contents

1. Introduction

Ballet dancers are high-performance athletes who are vulnerable to excessive rates of musculoskeletal injuries, where the highest incidence occurs in the foot and ankle region[1,2,3]. A 10-year retrospective cohort revealed that dancers experience at least one new injury every year of which foot and ankle injuries account for 40%[2]. Specifically overuse injuries are an issue for ballet dancers with an incidence rate of 2.82 injuries per 1000 dancing hours for females and 2.84 for males[4]. Plantar fasciitis is a common overuse injury in the foot region and the most common diagnosis attributed to heel pain[5,6]. Plantar fasciitis occurs due to excessive stress on the plantar fascia[7], which is a band of connective tissue that originates at the calcaneus and inserts on the tendons of the forefoot and proximal phalanges[8]. The plantar fascia functions as a shock absorber during activity and supports the longitudinal arch of the foot[6].

Excessive strain of the plantar fascia can be caused by overpronation because the plantar fascia elongates with 9 % during pronation in comparison with supination, which increases the tissue stress and the risk for developing plantar fasciitis[9]. In that regard, some ballet dancers do overpronate to make their foot and leg appear more turned out than they are capable of achieving through hip rotation and tibial torsion[10]. Additionally, high-arched feet (pes cavus) are related with decreased gastrocnemius, soleus, and Achilles tendon flexibility, which cause more tension in the plantar fascia during ankle dorsiflexion, which can result in plantar fasciitis. Pes cavus feet have also been associated with increased risk of developing plantar fasciitis[9] due to reduced assistance in dissipating the ground reaction forces (GRFs), which increases the load applied on the plantar fascia[11]. When ballet dancers are not wearing pointe shoes, they practice in soft shoes, which provides minimal support affecting the foot's musculature and stiffness. Hence, it increases the plantar musculature of the foot and promotes longitudinal arch stiffness, which may raise the arch.[12,13]

Excessive strain on the plantar fascia can be described with the "windlass mechanism"[14], which is a model that describes how the plantar fascia is pulled like a windlass during dorsiflexion of the metatarsophalangeal joint (MTPJ) because the arch rises, so the distance between the metatarsal heads and calcaneus shortens[14]. The windlass mechanism explains biomechanical factors and stresses that could cause plantar fasciitis[9]. The high plantar fascia stiffness prevents spreading of the calcaneus and metatarsus; however, that causes stresses on the plantar fascia[9]. Thus, plantar fasciitis is a result of increased plantar fascia tension[11], where it has been shown that increased dorsiflexion of the MTPJ increases strain of the plantar fascia[8,15,16]. Nonetheless, higher plantar fascia tensional load applies under the first MTPJ with a lateral decrement, so the fifth MTPJ experiences the lowest load during gait. Hence, maximal plantar fascia tension during gait occurs in the push-off phase when the toes dorsiflex the most while weight-bearing,[17] which is the principle of the windlass mechanism. Accordingly, dorsiflexion of the MTPJ is a basis position within ballet[18,19,20].

The aesthetics of ballet require repeated movements, which can cause micro-tears on the tissue because of workdays exceeding eight hours of dancing and little time for resting[1,21]. The movements and positions in ballet require an extreme range of motion (ROM) of the joints in the foot[1,18]. For instance, the demi-pointe position, where the dancer rises the heel off the ground, while the leg remains straight, requires 90° plantar flexion of the ankle[19] and 90° dorsiflexion of the MTPJ[18]. The foot is in demi-pointe position during ¾-Relevés, e.g. the Relevés Sur le Cou-de-Pied Derriere (see Figure 1a) and passes through demi-pointe in every Tendu (plantarflexion of the ankle joint and MTPJ), take-off and landing within a jump, e.g. Sautés in First Position (see Figure 1b), and rolling up and down to full pointe position. Additionally, high GRFs have been found during the landing phase of ballet jumps, particularly the Grand Jeté (see Figure 1c) and Grand Pas de Chat (see Figure 1d) [22,23], which puts stress on the plantar facsia[9] and thereby likely increases the risk for injuries[23].[*]

To date, research of the biomechanical risk factors, which can cause plantar fasciitis during ballet jump landings, is sparse. Thus, a deeper and more precise understanding of the loads acting on ballet dancers' feet are necessary to reduce the risk for developing plantar fasciitis. Therefore, the aim of the present study is to 1) investigate the MTPJ motion and lower limb loadings during different ballet jump landings and 2) suggest alternative implementations during ballet jump landings to prevent the occurrence of plantar fasciitis.

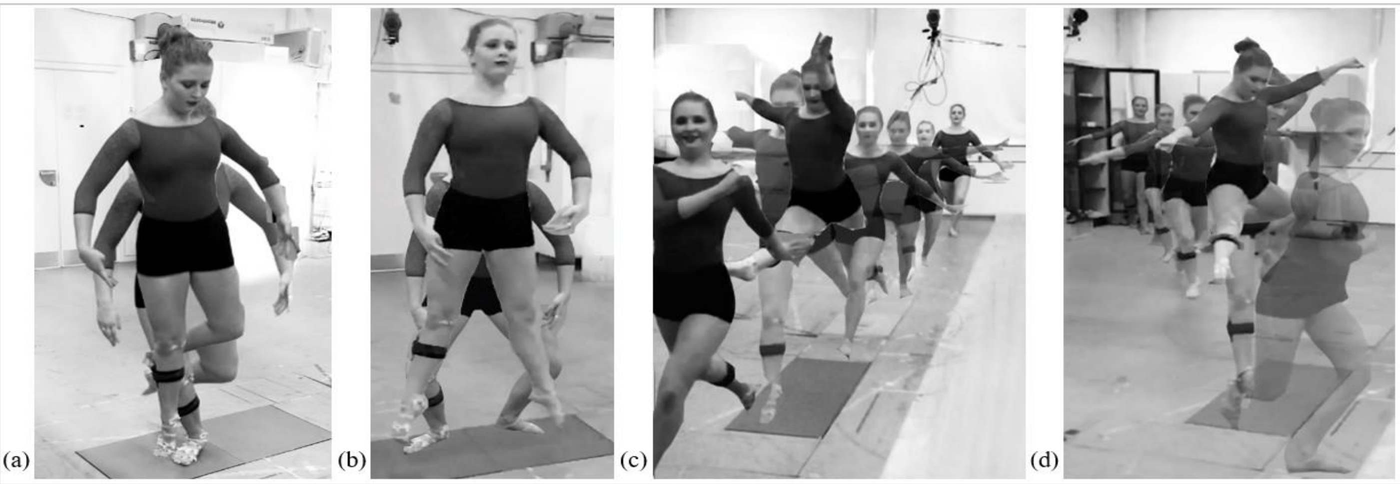

Figure 1. *(a) Relevés Sur le Cou-de-Pied Derriere, (b) Sautés in First Position, (c) Grand Jeté, (d) Grand Pas de Chat.*

[*] Videos of the jumps are available here: https://1drv.ms/u/s!AnTGwtMW0CARfm_8VNARIkuIbX8?e=jHWwMg

2. Methods

2.1 Participants

Four female vocational ballet dancers participated in the current study. Participants 1 and 2 (Group 1) were tested in a different laboratory, with a slightly different marker setup and experimental procedure, than Participants 3 and 4 (Group 2) who were tested in another laboratory. The physical characteristics of the dancers were (mean ± SD) age: 23.0 ± 5 years, height: 171.0 ± 9.1 cm, and body mass: 69.0 ± 12.2 kg. The dancers had performed classical ballet for 13.0 ± 9 years. Participants were excluded if they had a recent history of lower extremity injuries or pain that would impair their ability to dance, or if the participants had had any lower extremity surgery within the past two years. The participants were informed about the test protocol verbally and in writing before a written informed consent form was signed. The dominant leg was determined as the preferred leg used for single-leg landing when performing a Grand Jeté (see Figure 1c).

2.2 Foot Model

A three-rigid segment foot model was utilized in the current study, which was driven by retro-reflective markers. The segments included: (a) the shank, which included the tibia and fibula, (b) the hindfoot/midfoot, which included the calcaneus, talus, navicular, cuneiform, and metatarsals, (c) the forefoot, which included the phalanges. The following anatomical landmarks were tracked (see Figure 2 and Table 1).

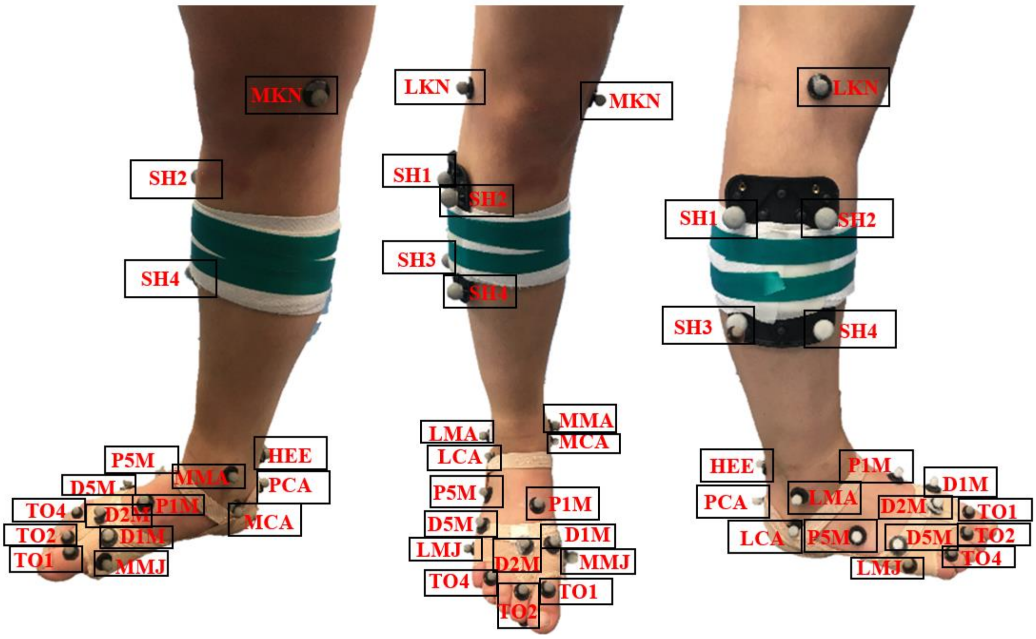

Figure 2. Medial, frontal, and lateral views of the respective retro-reflective markers of the foot model.

Table 1. Foot model including all utilized landmarks.

SEGMENT	MARKER	DESCRIPTION
SHANK	MKN	Medial condyle
	LKN	Lateral condyle
	SH1	First marker of the cluster on the shank
	SH2	Second marker of the cluster on the shank
	SH3	Third marker of the cluster on the shank
	SH4	Fourth marker of the cluster on the shank
	MMA	Medial malleolus
	LMA	Lateral malleolus
HINDFOOT/	PCA	Posterior aspect of the proximal calcaneus
MIDFOOT	HEE	Attached superior to PCA in alignment with MMA and LMA
	MCA	Medial aspect of the calcaneus in alignment with MMA
	LCA	Lateral aspect of the calcaneus in alignment with LMA
	P5M	Proximal part of the base of the fifth metatarsal
	P1M	Proximal part of the base of the first metatarsal
	D1M	Distal part of the head of the first metatarsal
	D2M	Distal part of the head of the second metatarsal
	D5M	Distal part of the head of the fifth metatarsal
	MMJ	Lateral border of the metatarsophalangeal joint (Group 1 only)
	LMJ	Medial border of the metatarsophalangeal joint (Group 1 only)
FOREFOOT	TO1	Middle part of the shaft of the first phalange
	TO2	Middle part of the shaft of the second phalange
	TO4	Middle part of the shaft of the fourth phalange
	MMJ	Lateral border of the metatarsophalangeal joint (Group 1 only)
	LMJ	Medial border of the metatarsophalangeal joint (Group 1 only)

2.3 Experimental Overview

Kinematic data of the dominant lower extremity was recorded using an eight-camera three-dimensional motion capture system collecting at 250 Hz (Opus, Qualisys AB, Gothenburg, Sweden). GRF data were collected at 1000 Hz using two force platforms (AMTI) for Group 1, while GRF data were collected at 1000 Hz using one force platform (Kistler) for Group 2.

The participants' mass and height were measured when they arrived at the laboratory. They were then dressed in spandex shorts and foot thongs (see Figure 3), so most of the foot was bare for markers to be attached directly onto the skin. Suede pads underneath supported the foot similar to that of soft ballet shoes. Group 1's marker setup consisted of a four-marker cluster, which was placed on the lateral side of the shank and eighteen retro-reflective markers (9.5 mm Ø), which were placed on selected anatomical landmarks on the shank and foot of the dominant leg (see Figure 2). Group 2 had a four-marker cluster placed on the lateral side of the shank and thirteen retro-reflective markers (9.5 mm Ø) placed on selected anatomical landmarks on the shank and foot of the dominant leg (see Figure 2). However, three virtual markers were created on the first, second, and fourth toe, respectively, using a digitizing pointer (C-Motion Inc.) in the static standing trial. All participants had the markers placed according to Table 1. The retro-reflective markers were secured using double adhesive tape and additional fixomull tape was wrapped around the markers' plates to avoid them falling off. After the markers were attached, the participants were instructed to complete a 30-min warm-up session with specific barre exercises before a static trial (standing reference) was collected.

Figure 3. *The foot thong, worn by the dancers during the tests.*

2.4 Test Protocol

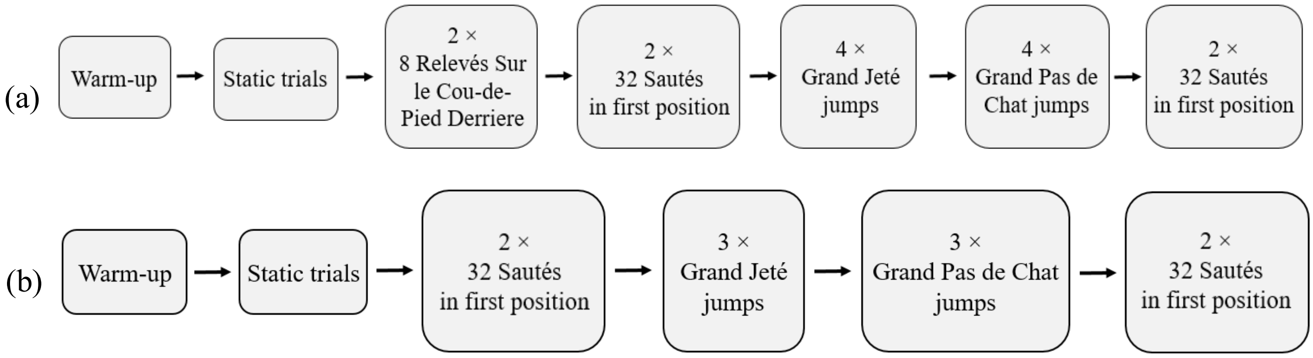

Figure 4. *Flow diagram of the test protocol for Group 1 (a) and Group 2 (b), respectively.*

Following the warm-up and static trials, the data collection began (see Figure 4). The first movement consisted of eight Relevés Sur le Cou-de-Pied Derriere (see Figure 1a) twice on the dominant leg with a frequency of 120 bpm (Group 1 only). Subsequently, Group 1 stood with one foot on each force platform, while Group 2 stood with both feet on the same platform and performed 32 Sautés in First Position (see Figure 1b) twice with a frequency of 180 bpm. The first four and the last four of the total 32 jumps were used for further analysis. After the Sautés in First Position, Group 1 performed a Grand Jeté (see Figure 1c) four times, while Group 2 performed the Grand Jeté three times.

Thereafter, Group 1 performed a Grand Pas de Chat (see Figure 1d) four times, whereas Group 2 performed the Grand Pas de Chat three times. Finally, the dancers performed 32 Sautés in First Position twice, where the first four and the last four of the total 32 jumps for each trial were used for further analysis. The participants practiced each movement at least once, or until the procedures fell comfortable prior to data collection. Furthermore, the dancers were allowed to rest in-between each trial for as long as desired. Successful trials were defined as landing with the foot firmly placed within the force platform, keeping balance, proper approaching steps, and maintaining the timing of the music. The participants' techniques were neither coached nor corrected when performing the respective movements.

The Grand Jeté and Grand Pas de Chat jumps were selected based on findings from pilot work, which examined movements most likely to generate the highest loadings on the foot, ankle, and lower limbs. The 32 Sautés in First Position sections were introduced as a novel fatigue task based on ballet observations and feedback, since it contains repetitive MTPJ motion and high lower limb loading, which might induce fatigue. The Relevés Sur le Cou-de-Pied Derriere was introduced based on observations and feedback, which examined that movement to generate large MTPJ dorsiflexion angles while weight bearing.

2.5 Data Analysis

The marker trajectories were manually identified using Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden) before the trials were exported as C3D files and imported into Visual 3D (C-motion, Inc., Germantown, USA) for data processing and analysis. Mass and height were initially defined for each participant. Furthermore, the three virtual markers made with the digitizing pointer were defined for Group 2, so that all markers were visible throughout all trials. In addition, the segments of the shank, entire foot, hindfoot/midfoot, and forefoot were defined (see Figure 5). The kinetic data were filtered with a Butterworth low-pass filter with a cut-off frequency of 150 Hz, while the kinematic data were filtered with a Butterworth low-pass filter with a cut-off frequency of 14 Hz. The stance phase was defined as whenever the vertical

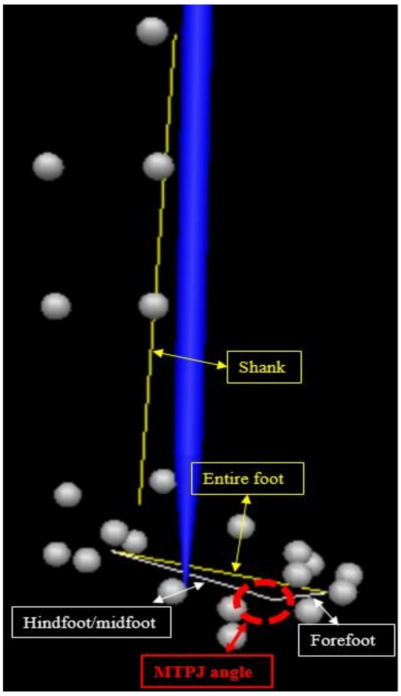

Figure 5. Illustration of the calculated MTPJ angle and the respective segments.

ground reaction force (vGRF) exceeded a threshold of 15 N. The stance phase data were normalized to 101 data points (0-100 %).

The global coordinate system had the y-axis parallel to the running direction (anterior-posterior), the x-axis was in the medial-lateral direction, and the z-axis oriented in the vertical direction. The orientation of the segment’s local coordinate systems were defined similar to the global coordinate system in the standing reference trial. The MTPJ angle (see Figure 5) was calculated for Participants 1 and 2 using an XYZ Cardan sequence, where a negative angle defined dorsiflexion of the MTPJ. The static trials identified the standing MTPJ angles as -25.1° for Participant 1 and -21.0° for Participant 2.

2.6 Statistical Analysis

The vGRF and ankle power data were normalized to body weight (N/BW and W/BW) and the vGRF peaks were defined for both the Grand Jeté, Grand Pas de Chat, and Sautés in First Position landings for all participants. Additionally, the vGRF peaks were defined for the Relevés Sur le Cou-de-Pied Derriere, while landing on flat foot and during ¾-pointe position. The max MTPJ dorsiflexion angle and MTPJ angular velocity were determined over the entire stance phase and identified at peak in vGRF for Participants 1 and 2. vGRF, MTPJ angle, and ankle power curve patterns were identified for all movements. The Sautés in First Position and Relevés Sur le Cou-de-Pied Derriere were described with mean (± SD) curves due to the multiple jump sequences, which provided decent graphs. However, the Grand Jeté and Grand Pas de Chat curves were identified with a mean curve and a curve for each trial in every graph due to missing timing consistency between the jumps, as it was observed that a mean curve distorted the actual peak values.

3. Results

3.1 Grand Jeté and Grand Pas de Chat Landings

vGRF peaks are higher during Grand Pas de Chat landings compared with the Grand Jeté landings for Participants 3 and 4, whereas Participant 1 does not indicate any differences and Participant 2 demonstrates higher vGRF peaks during Grand Jeté landings. The negative ankle power peaks during initial contact are higher for the Grand Pas de Chat landings compared with the Grand Jeté landings for all participants, where Participants 3 and 4 indicate much higher negative ankle power peaks compared with Participants 1 and 2 for both the Grand Jeté and Grand Pas de Chat landings. ROM increases in the Grand Pas de Chat landings compared with Grand Jeté landings, where the two participants demonstrate higher max MTPJ dorsiflexion angles as well as lower MTPJ dorsiflexion angles at vGRF peaks. Additionally, Participant 1 shows lower MTPJ dorsiflexion angles at vGRF peaks compared with Participant 2. Moreover, Participant 2 demonstrates much higher MTPJ angular velocities at vGRF peaks compared with Participant 1 (see Table 2 and Figure 6).

Table 2. *Grand Jeté and Grand Pas de Chat peak values and values at vGRF peak.*

	Mean (±)	*vGRF peaks (N/BW)*	*MTPJ angle (°) at vGRF peaks*	*MTPJ angular velocity (°/s) at vGRF peaks*	*Max MTPJ angle (°)*	*Max MTPJ angular velocity (°/s)*	*Max negative ankle power peaks (W/BW)*
Grand Jeté	Participant 1	4.2 (± .1)	-9.5 (± .8)	-48.1 (± 38.4)	-58.8 (± .8)	-1988.2 (± 720.4)	-3.7 (± .2)
	Participant 2	4.1 (± .5)	-24.9 (± 1.4)	-436.8 (± 107.8)	-60.9 (± 2.1)	-1460.0 (± 814.5)	-4.5 (± .3)
	Participant 3	4.2 (± .8)					-6.5 (± .7)
	Participant 4	4.3 (± .4)					-7.3 (± .7)
Grand Pas de Chat	Participant 1	4.2 (± .4)	-5.5 (± 1.6)	-120 (± 17.1)	-65.1 (± 8.1)	-1182.0 (± 142.4)	-4.2 (± .1)
	Participant 2	3.8 (± .4)	-19.2 (± 2.6)	-312.7 (± 57.4)	-62.5 (± 4.5)	-1383.9 (± 370.1)	-4.9 (± .5)
	Participant 3	5.3 (± .5)					-8.2 (± .2)
	Participant 4	6.5 (± .9)					-9.9 (± .5)

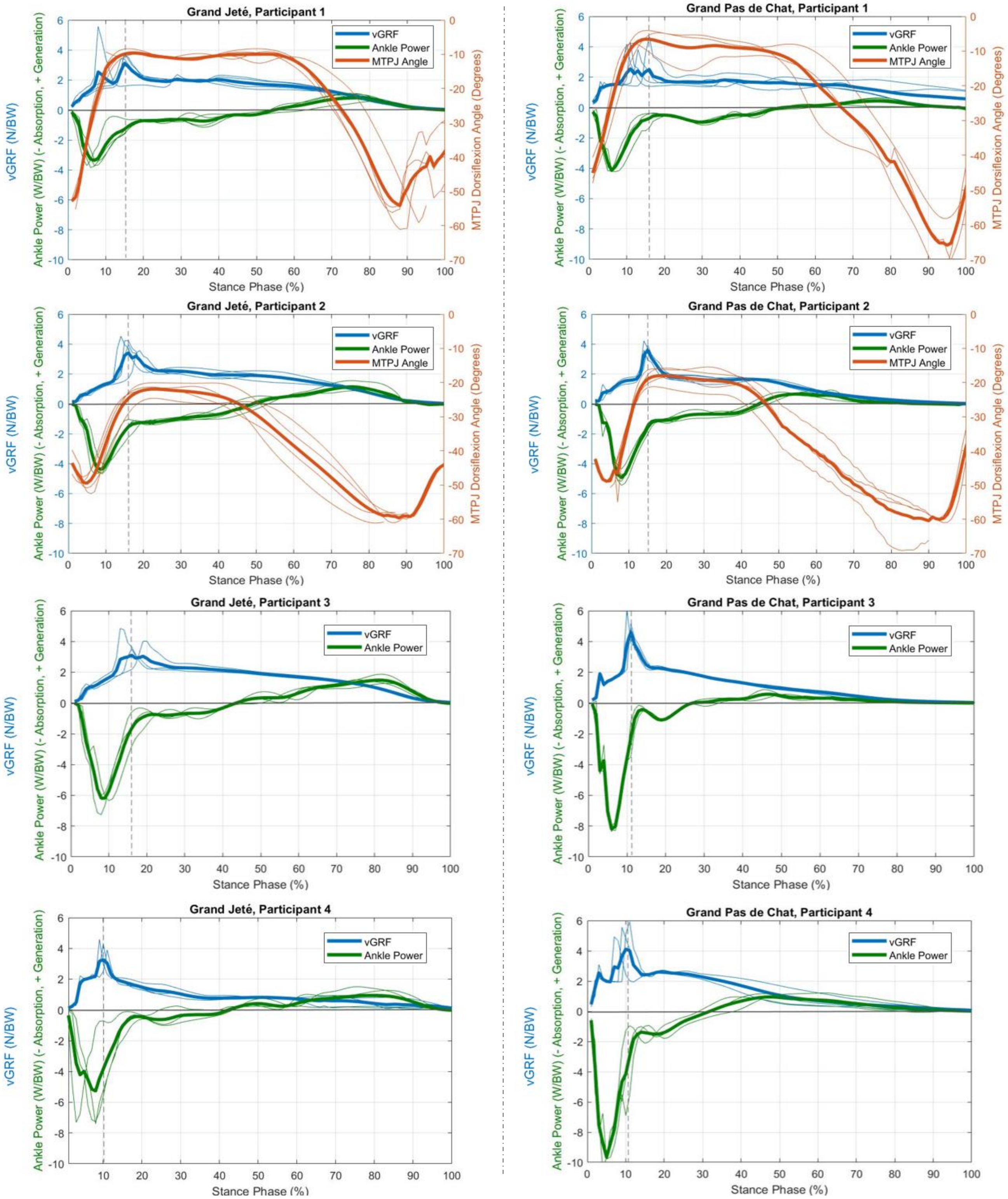

Figure 6. *Grand Jeté landings on the left side and Grand Pas de Chat landings on the right side of the figures for the four Participants. The graphs show the curves for vGRF and ankle power on the left y-axis. The right y-axis illustrates the MTPJ dorsiflexion angle for Group 1. Dashed vertical lines in every graph indicate vGRF peaks of the mean curves. The graphs represent the mean curves (thick lines) and every jump landing (thin lines).*

3.2 Relevés Sur le Cou-de-Pied Derriere

vGRFs are higher during flat foot landings compared with impact on ¾-pointe position during the Relevés. The dorsiflexion of the toes in ¾-pointe position results in large MTPJ angles, whilst vGRF peaks exceed bodyweight. The graphs illustrate that Participant 2 keeps a steadier MTPJ dorsiflexion angle during ¾-pointe position in the Relevés compared with Participant 1. Both negative and positive ankle power are higher during landing and push-off from a flat foot position compared to those from ¾-pointe position (see Table 3 and Figure 7).

Table 3. *Relevés Sur le Cou-de-Pied Derriere values at vGRF peak when landing on ¾-pointe and on flat foot as well as peak values during the entire Relevés.*

Relevés Sur le Cou-de-Pied Derriere	**Mean (±)**	Impact on ¾-pointe			Landing on flat foot			Max during the Relevés	
		vGRF peaks (N/BW)	*MTPJ angle (°) at vGRF peaks*	*MTPJ angular velocity (°/s) at vGRF peaks*	*vGRF peaks (N/BW)*	*MTPJ angle (°) at vGRF peaks*	*MTPJ angular velocity (°/s) at vGRF peaks*	*Max MTPJ angle (°)*	*Max MTPJ angular velocity (°/s)*
	Participant 1	1.7 (± .1)	-53.3 (± 6.4)	-85.3 (± 46.3)	2.4 (± .3)	-8.2 (± 2.2)	-51.8 (± 37.1)	-63.9 (± 3.2)	-958.3 (± 262.7)
	Participant 2	1.5 (± .1)	-58.9 (± 2.1)	-78.0 (± 83.9)	2.6 (± .2)	-18.9 (± 1.7)	-60.4 (± 47.1)	-61.9 (± 2.3)	-460.6 (± 187.4)

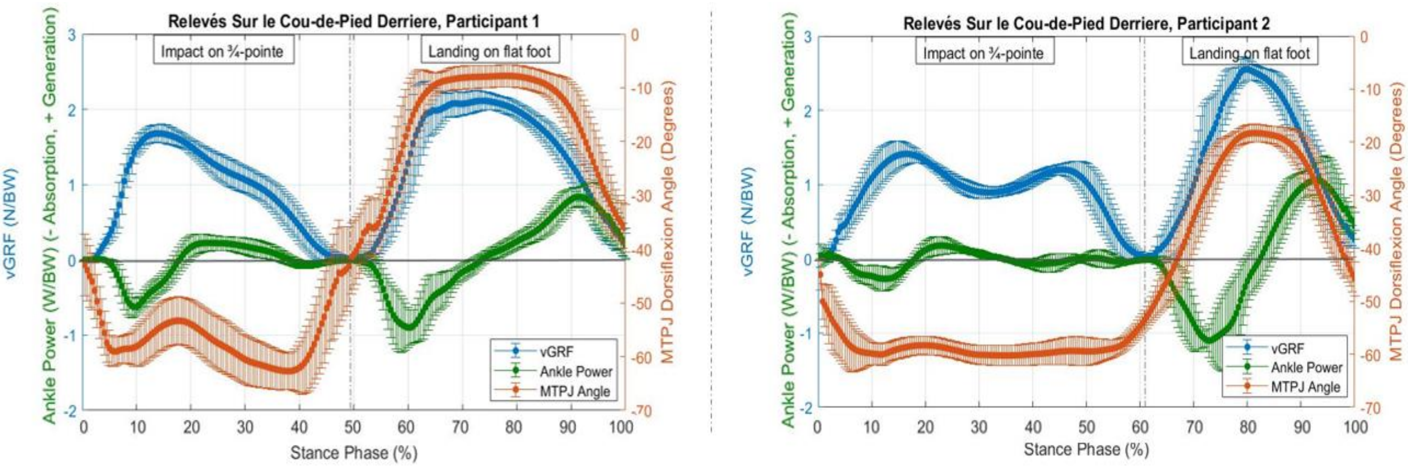

Figure 7. *The graphs show the mean (± SD) curves for 2 × 8 Relevés Sur le Cou-de-Pied Derriere Graphs for Participants 1 and 2, respectively. vGRF and ankle power are illustrated on the left y-axis, while the right y-axis illustrates the MTPJ dorsiflexion angle. Dashed vertical lines in the graphs separate the two sequences of the jump: impact on ¾ -pointe position, and landing on flat foot, respectively.*

3.3 Sautés in First Position

Similar vGRF peaks are shown for Participants 1 and 3 between the first and last jump sections; however, Participants 2 and 4 demonstrate higher vGRF peaks during the first jumping section compared with the last. Participants 1 and 2 indicate higher max MTPJ angles and max MTPJ angular velocities during the last jumping sections in comparison with the first. Participants 1, 4, and 3 especially show higher ankle power for both jump sections than Participant 2, who is the only one demonstrating within-participant deviations between the first and last jumping sections with respect to ankle power (see Table 4 and Figure 8).

Table 4. *Sautés in First Position peak values and values at vGRF peak for the first two jumping sections (First) and the last two jumping sections (Last).*

	Mean (±)	*vGRF peaks (N/BW)*	*MTPJ angle (°) at vGRF peaks*	*MTPJ angular velocity (°/s) at vGRF peaks*	*Max MTPJ angle (°)*	*Max MTPJ angular velocity (°/s)*
Sautés in First Position	Participant 1 (First)	3.0 (± .4)	-15.4 (± 2.4)	- 83.2 (± 78.0)	-63.3 (± 4.5)	-830.1 (± 185.2)
	Participant 1 (Last)	2.9 (± .4)	-15.6 (± 3.6)	-105.2 (± 73.0)	-66.4 (± 4.5)	-941.9 (± 181.8)
	Participant 2 (First)	3.3 (± .5)	-19.4 (± 1.9)	-87.7 (± 64.4)	-55.4 (± 4.5)	-546.3 (± 73.2)
	Participant 2 (Last)	2.6 (± .2)	-20.9 (± 1.5)	-22.5 (± 56.8)	-57.0 (± 3.2)	-594.9 (± 112.1)
	Participant 3 (First)	3.4 (± .4)				
	Participant 3 (Last)	3.3 (± .3)				
	Participant 4 (First)	3.1 (± .5)				
	Participant 4 (Last)	2.8 (± .3)				

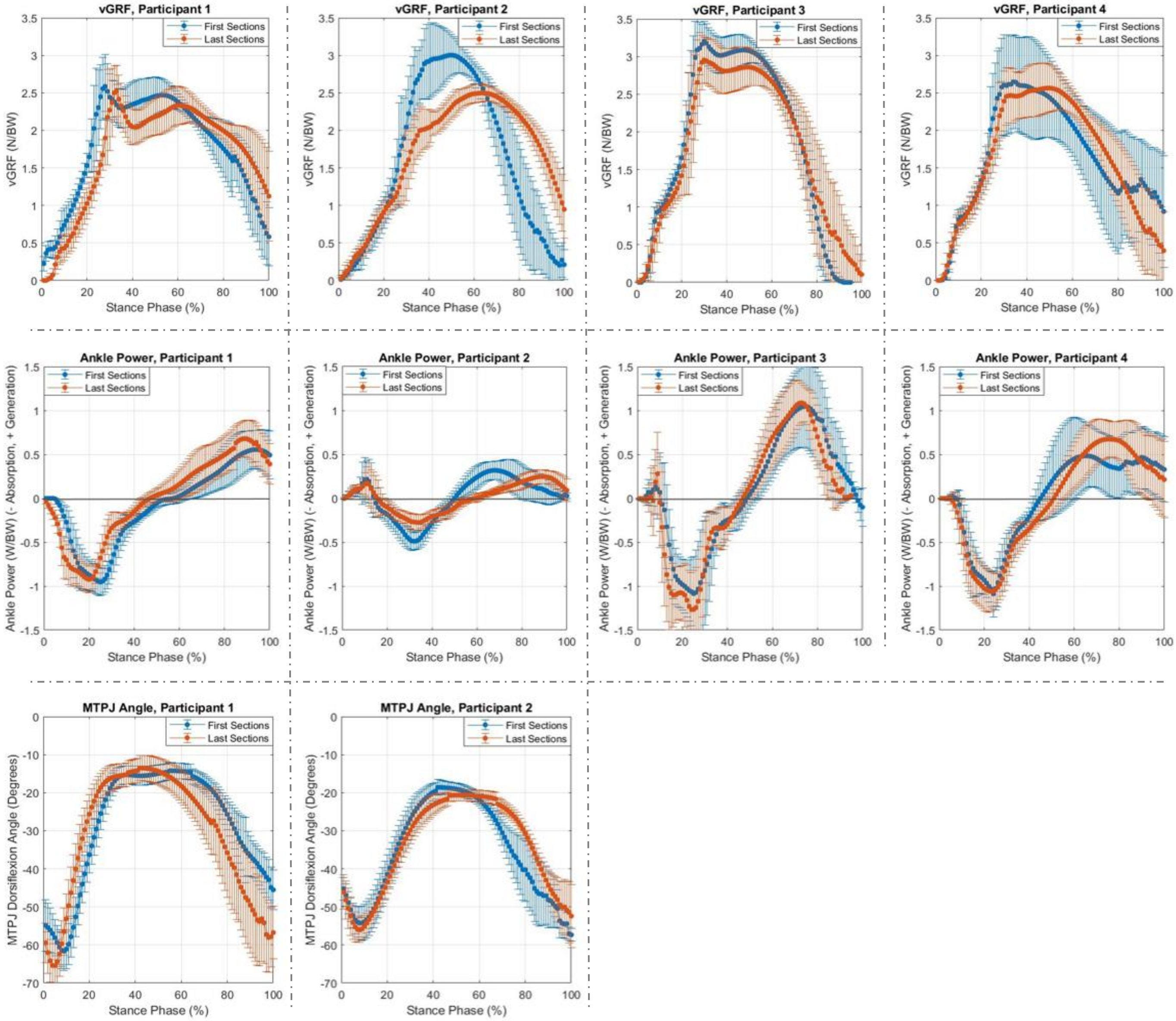

Figure 8. *The graphs show the mean (±) curves for the first two Sautés in First Position sections (blue) and the last two sections (orange). The rows separate vGRF, ankle power, and MTPJ angle, respectively, whilst the columns separate the four Participants.*

4. Discussion

The aim of this study was to 1) investigate the MTPJ motion and lower limb loadings during different ballet jump landings and 2) suggest alternative implementations during ballet jump landings to prevent the occurrence of plantar fasciitis.

4.1 Biomechanical Risk Factors Related to Plantar Fasciitis

Plantar fasciitis is a result of increased biomechanical stresses on the plantar fascia[11,24], where increased dorsiflexion of the MTPJ increases the plantar fascia strain[15,16,25] and missing dissipation of GRFs increases the load on the plantar fascia[11]. Hence, high GRFs and large MTPJ dorsiflexion angles can contribute to developing plantar fasciitis. In consistency with findings from previous studies[22,23], this study revealed high vGRFs during the Grand Jeté and Grand Pas de Chat jump landings. However, during vGRF peaks, the Grand Pas de Chat landings showed lower MTPJ dorsiflexion angles compared with the Grand Jeté landings for Participants 1 and 2. The lower MTPJ dorsiflexion angle may help with the force dissipation within the tissue due to an unwinding of the windlass mechanism[14], and could thereby be associated with a lower risk for developing plantar fasciitis with the entire foot assisting in absorbing the GRFs[11]. In that regard, Participant 2 demonstrates much larger MTPJ dorsiflexion angles at vGRF peaks for all jump landings throughout the test protocol compared with Participant 1, despite the fact that Participant 2 showed a smaller MTPJ dorsiflexion angle during the static reference trial (21.0°) compared to Participant 1 (25.1°). Accordingly, Participant 2 may apply unnecessary load on the plantar fascia as a consequence of having tighter calf muscles, which is associated with the occurrence of plantar fasciitis[26,27]. Furthermore, Participant 2 indicates much higher MTPJ angular velocities at vGRF peaks for both the Grand Jeté and Grand Pas de Chat landings, which indicates that the MTPJ angle has not reached full stance during vGRF peak, whereby additional stresses may be applied to the plantar fascia.

The results show higher negative ankle power peaks during the Grand Pas de Chat landings compared with the Grand Jeté landings, whereas relatively small ankle power peaks occur during the Relevés Sur le Cou-de-Pied Derriere and Sautés in First Position. Thus, both the Grand Pas de Chat and Grand Jeté landings demand high eccentric power, though the results indicate large between-participant deviations. It has been suggested that runners can adapt their running technique to minimize the ankle joint muscle damage by changing the plantar flexion moment[28], which likewise may be the case for ballet dancers.

Despite slightly higher vGRF means during the first Sautés in First Position sections compared with the last, no major within-participant differences between the first and last sections regarding any parameter were registered for any participants. However, a minimal increase from the first sections to the last in MTPJ angle at vGRF peak, max MTPJ angle, and max MTPJ angular velocity for Participants 1 and 2 indicate that multiple repetitions do not reduce MTPJ angles and angular velocities. Consequently, repeated repetitions intensify the loading frequency on the lower extremities, which may contribute to the occurrence of injuries[29]. Nevertheless, the present study's novel fatigue test may not reflect an actual training session, where the professional dancers record 500-600 jumps every day in class and rehearsals[30]. However, if an athlete pushes beyond the point of fatigue, damage to muscles and ligaments is possible because overuse injuries result from repetitive sub-traumatic loading[31]. The Relevés Sur le Cou-de-Pied Derriere may be a particular high-risk movement for developing plantar fasciitis due to vGRFs exceeding body weight during ¾-pointe position with large MTPJ dorsiflexion angles multiple times in a row, which would cause repetitive sub-traumatic loading to the plantar fascia.

4.2 Preventing Plantar Fasciitis

Muscle strain injuries are often a result of powerful eccentric contractions[31]. However, stronger muscles are more resistant to damage due to a higher cross-sectional area and other tissue adaptations[32], which is why specificity of the training is important to develop strength in the muscles that are exposed to high demands[31]. Furthermore, sprung floors may reduce the eccentric muscle contraction during ballet jump landings[33], in which case force reduction floors have been associated with decreasing negative joint power[34] and minimizing injury risks[35]. Additionally, reduced floor stiffness reduces the negative peak ankle and knee angular velocities, which can be a contributory factor to reduce dance-related overuse injuries[36]. In the light of this, utilizing a sprung floor may reduce the MTPJ negative angular velocity peaks similarly, and thereby reduce the risk of developing plantar fasciitis. Nonetheless, many major stages contain a sloped floor to present more of the performance to the audience, which can cause additional stress to the dancers' ligaments and joint[37]. Therefore, optimizations of the stages to favour the audience, but also minimize dancers' injury risks should be an important consideration. Sprung floors are present in professional ballet schools; however, when sprung floors are not available, the dancers should consider jumping less. While sprung floors reduce the risk for injuries within ballet dance, ballet dancers wear minimal footwear[3]. Unlike athletic shoes, soft ballet shoes and pointe shoes do not contain any shock-absorbing midsole materials[33]. Increasing the cushioning of the ballet shoes may contribute to attenuate some of the loads furtherly; however, the articulation and aesthetics of the foot, which is essential to ballet technique, may be affected negatively by increasing the cushioning. In addition to sprung floors and shoe cushioning, the dancers may be able to control their landings by training eccentric muscle contractions. Muscle and tendon structures are adaptable to chronic exposures, which is why eccentric-resistance exercise protocols can be a solution[38].

Participant 2 demonstrates larger MTPJ dorsiflexion angles and MTPJ negative angular velocities during vGRF peaks and greater negative ankle power peaks for both the Grand Jeté and Grand Pas de Chat landing compared with Participant 1. In this regard, between-participant variations occur, which can be a result of training and personal strength. For instance, Participant 1 may have stronger and more adapted muscles and ligaments for the required ballet jump landing demands to reduce the impact loadings and MTPJ dorsiflexion angles before vGRF peaks compared with Participant 2. Thus, improved landing techniques may reduce the MTPJ dorsiflexion angle and MTPJ angular velocity at vGRF peaks, which may prevent plantar fasciitis. Hence, larger MTPJ dorsiflexion angles at vGRF peaks occur for the Grand Jeté landings compared with the Grand Pas de Chat landings. Therefore, further investigation of the different landing techniques may be beneficial for the dancers to make the Grand Jeté landings more similar to the Grand Pas de Chat landings and thereby reduce MTPJ dorsiflexion angles at vGRF peaks.

In addition, MTPJ ROM may be used to indicate fatigue as joint ROM can be impaired immediately after exercise, which also will be reflected in reduced ROM later on[39]. Therefore, decreased max MTPJ angles can be a result of fatigue and damage to the plantar fascia, in which case longer recovery periods are needed and high-risk movements should be avoided or reduced in frequency.

4.3 Testing Potential Interventions

The suggested interventions should be tested to gain knowledge about the applicability and possible improvements[40]. The test should include the same dancers, test protocol, and laboratory settings; however, the floor should be replaced with a sprung floor. Furthermore, the dancers should have accomplished a specific training program, developed with expertise from a physical therapist, to improve muscle strength around the MTPJ and ankle joint to reduce impact angular velocities and reach full stance before vGRF peaks. Additionally, alterations to ballet shoes to increase midfoot cushioning and support should also be explored. The test parameters should be identical, where reduced negative ankle power peaks and reduced MTPJ dorsiflexion angles and MTPJ negative angular velocities at vGRF peaks should occur for the interventions to be beneficial.

5. Future Directions

In case the test indicates positive outcomes, the interventions need to be adopted by the ballet dancers to be effective. In that regard, awareness of the injury culture for everyone in a ballet company including the ballet master, principal dancers, soloists, corps de ballet, and all of the staff is essential to understand and implement the interventions[40]. Nonetheless, knowledge will most likely not be enough to change the dancers' footwear choices and training programs. In fact, dancers prefer to utilize footwear with little cushioning because feeling the floor is essential when dancing[1]. However, the ballet master can require an implementation of specific training programs, while safety guidelines can demand minimum cushioning effects for ballet footwear, though cushioned footwear might affect the dancers' behaviour negatively. Ultimately, the implemented interventions need to be tested in a prospective study design to evaluate the applicability and effectiveness.

6. Conclusion

The preliminary data obtained from the current explorative study indicates high vGRF peaks during the Grand Jeté and Grand Pas de Chat landings. The Grand Pas de Chat landings illustrate higher negative ankle power peaks whilst the Grand Jeté landings provide larger MTPJ angles at peak in vGRF, which may increase the risk for developing plantar fasciitis. Stronger muscles around the MTPJ and ankle joint may attenuate the high eccentric muscle forces together with sprung floors and additional shoe cushioning, which may also reduce the angular velocities of MTPJ and attenuate some of the loads. Implementing wide use of sprung floors, increasing midsole shoe cushioning in ballet shoes, and accomplish specific eccentric muscle training programs may reduce the ankle joint and MTPJ loadings during landings, and thereby reduce the risk for developing plantar fasciitis.

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