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The effect of pointe shoe deterioration on foot and ankle kinematics and kinetics in professional ballet dancers

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Abstract

Dancing en pointe significantly increases the risk of lower limb injuries by placing the foot and ankle joint in unfavorable positions. The pointe shoe, worn predominantly by female ballet dancers may aid movement and acts as a major stabilizer of the foot. The deterioration in pointe shoe structure with excessive wear may increase a dancer's risk of ankle and foot related injuries by placing excessive load on the joints when the foot is poorly aligned. The purpose of this study was to investigate differences in foot and ankle kinetics and kinematics between new and worn pointe shoes. Fifteen professional ballet dancers completed a series of bourrées (walking en pointe) in both new and worn pointe shoes (> 20 hours wear). Force and pressure analyses determined peak ground reaction force and centre of pressure velocity. A 2D kinematic analysis determined the magnitude of mid-foot flexion and ankle plantarflexion. The worn pointe shoe caused significantly greater mid-foot flexion ($P < 0.01$) and ankle plantarflexion ($P < 0.01$) en pointe compared to the new pointe shoe. No significant changes in peak force ($P = 0.855$) or centre of pressure velocity ($P = 0.297$) were observed between conditions. The reduced structural integrity of the worn pointe shoe may be a causal factor for kinematic changes and subsequent pain and lower limb injuries in professional dancers.

Keywords: Ballet, Dancing, Kinetics, Kinematics, Injury.

1. Introduction

Classical ballet is an exceptionally physical performing art form. While audiences may enjoy the grace and artistic merit of ballet, this demanding activity requires repetitious, rigorous training and performance schedules (Yan, Hiller, Smith, & Vanwanseele, 2011), which may contribute to a high annual incidence of injuries (67%-95%) in this group (Byhring & Bo, 2002). In female dancers, overuse injuries to the lower extremities are the most prevalent (Allen, Nevill, Brooks, Koutedakis, & Wyon, 2016). In particular, the extreme positions of pointe work can lead to overuse injuries of the foot and ankle, which is reported to be experienced by 14-57% of female ballet dancers (Smith *et al.*, 2016; Caine, Goodwin, Caine, & Bergeron, 2015; Leanderson *et al.*, 2001). During pointe work, full ankle plantarflexion causes weight bearing forces to be transmitted from the distal phalanges through the metatarsals and stretching soft tissues of the foot. This may explain the high incidence of foot muscle strains and tears, mid-foot pain, and metatarsophalangeal joint pain in this group (Allen *et al.*, 2012; Macintyre & Joy, 2000).

The pointe shoe is designed to assist the ballet steps executed whilst in plantarflexion, protecting the feet from impact forces and stabilising the performer (Walter, Docherty, & Schrader, 2011). The toe box of the pointe shoe is constructed from layers of hessian, glue and fabric (Kadel, 2006), which must be strong enough to support the dancer en pointe, but be malleable enough to allow articulation of the joints of the foot and ankle. However, in several cases, professional dancers are required to change their pointe shoes once or twice per performance, due to rapid deterioration of the shoe's integrity (Cunningham, DiStefano, Kirjanov, Levine, & Schon, 1998; Yan *et al.*, 2011). With this deterioration comes a softening of the shank and the satin outer-lining, which causes reduced rigidity of the pointe shoe.

Previous dance studies have found injuries can be caused predominantly by inadequate stabilisation of the foot and ankle (Yan *et al.*, 2011). A worn pointe shoe with reduced structural integrity may reduce the ability of a dancer to correct postural sway, resulting in accelerated rates of muscle fatigue, ankle sprains or falls (Beynnon, Murphy, & Alosa, 2002). Additionally, during pointe work a dancer is required to maintain full plantarflexion of the ankle, extending through the mid-foot to the toes. This is achieved predominantly by movement of the talocrural joint and to lesser extent by bones of the foot (Russell, Shave, Kruse, Koutedakis, & Wyon, 2011). A worn pointe shoe, which has increased flexibility, may no longer be able to support the foot and ankle in the required position, and as a result, hyperplantarflexion of the talocrural joint and excessive mid-foot flexion may occur. Considering joints and ligaments of the foot are not designed to accept excessive loading, these changes could lead to the compression of soft tissue structures (Moser, 2011) and strains in the midfoot ligaments (Russell, Kruse, Koutedakis, McEwan, & Wyon, 2010a).

Injury in this population may also be caused by a lack of sufficient shock absorbing material, which may be exacerbated in a worn pointe shoe. A new pointe shoe may contribute to the attenuation of ground reaction forces (Kong, Candelaria, & Smith, 2009). Indeed, ground reaction forces have been linked to several injuries, including stress fractures which have a high incidence rate in ballet dancers (Hincapié, Morton, & Cassidy, 2008; Ferber, McClay, Hamill, Pollard, & McKeown, 2002). Research has found that cushioning properties of footwear may reduce the magnitude of ground reaction forces (Zhang, Clowers, Kohstall, & Yu, 2005). However, several researchers have also found that the characteristic of a shoe has no effect on the impact from a jump (Fu, Liu, & Zhang, 2013). Indeed, the strongest factor in lowering impact forces is greater knee flexion (Derrick, 2004) and since a considerable amount of pointe work is performed during knee extension, less absorption of impact force may be

expected, putting the dancers at greater risk of joint injury (Potthast, Brüggemann, Lundberg, & Arndt, 2010).

The incidence of foot and ankle related injuries in dancers is high, and may be exacerbated by the deterioration of the pointe shoe used during ballet dancing. In light of a void in knowledge about how pointe shoe usage over time affects the mechanical properties of the shoe, the purpose of this study was to investigate differences in foot and ankle kinetics and kinematics between new and worn pointe shoes. These results may provide valuable information on risk factors for injury in professional ballet dancers.

2. Methods

2.1 Participants

Fifteen professional female ballet dancers (age: 26 ± 4 years; height 1.63 ± 0.61 m; mass: 51.7 ± 3.8 kg), from UK leading ballet companies participated in this study. All participants had a minimum of three years professional dance experience in pointe shoes, and took part in a minimum of 25 hours of ballet training per week. The study was approved by institutional ethics committee following guidelines from the Declaration of Helsinki.

2.2 Experimental setup

The study utilised a randomized cross-over design, whereby participants performed a series of dance bourrées wearing new and worn (with approximately 20 hours of wear) pointe shoes, whilst synchronized measurements of foot and ankle kinematics and underfoot kinetics were recorded. Twenty hours was considered to represent a “worn” pointe shoe, based on the intense

work performed by the dancers in this study, who typically changed shoes 10 times per month, together with the approximate 12 hour lifespan of the pointe shoe (Cunningham *et al.*, 1998). For To measure changes in mid-foot flexion and ankle plantarflexion, reflective markers were placed on the lateral femoral epicondyle, lateral malleolus, on the outside of the shoe at the head of the fifth metatarsal, navicular and calcaneus of the right leg. A 2D video camera (Panasonic HC-V210 HD camcorder, Panasonic UK Ltd., Berkshire, UK) sampling at 50 Hz was placed perpendicular to the dancer, with the optical axis aligned with the lateral malleolus of the right leg. A force platform sampling at 1000 Hz (Kistler 9287BA Force Platform, Kistler Instruments Ltd. Hampshire, UK) was integrated into the floor, to measure vertical ground reaction forces. A pedobarograph (RSScan 0.5m USB2 Plate, RS Scan Ipswich, UK) positioned directly on top of the force platform recorded centre of pressure position (Figure 1). Custom-made flooring was used to embed the pedobarograph and ensure a level surface. A marker was placed at each diagonal edge of the pedobarograph to mark the direction of travel. This ensured each dancer did not move out of plane during the trials.



Figure 1. Experimental setup of a dancer performing a series of bourrées across the force plate and pedograph whilst simultaneous kinematic measures are recorded

2.3 Procedures

Following a ballet-specific warm-up, each dancer performed three sets of bourreés in each condition. The bourrée required the dancer to rise onto pointe, with one leg placed in front of the other and the knees and ankles in full extension. Dancers were instructed to begin with the left leg and travel from the first to second markers across the force platform and pedobarograph, whilst keeping the arms in first position (fingers almost touching, arms forming an oval shape). Approximately 3-4 steps were performed by each dancer across the force platform with one of these steps also contacting the pedobarograph. The step which simultaneously landed on both the force platform and pedobarograph was used for analysis. To maintain a consistent tempo and step length between trials, participants were asked to match steps to an excerpt of Tchaikovsky's *Swan Lake* score. A mandatory 15 minutes rest period was given before participants changed footwear and the second condition was performed.

2.3 Data analysis

Ankle plantarflexion and mid-foot flexion were calculated using video analysis software (0.8.17, Kinovea Open Source, www.kinovea.com). The anterior angle between the fifth metatarsal, lateral femoral epicondyle and the lateral malleolus was calculated to be ankle plantarflexion angle (Figure 2, left). Mid-foot flexion was calculated according to Leardini's *et al.* (2007) foot model, which has been shown to be a valid and repeatable method for standardising the description of foot segment kinematics (Myers, Wang, Marks, & Harris, 2004). The position of the navicular as a percentage of total pointe shoe length was calculated and marked on the foot. Using the calcaneus and fifth metatarsal as reference points the anterior angle was calculated (Figure 2, right). Both angles were calculated at the point of maximal plantarflexion.

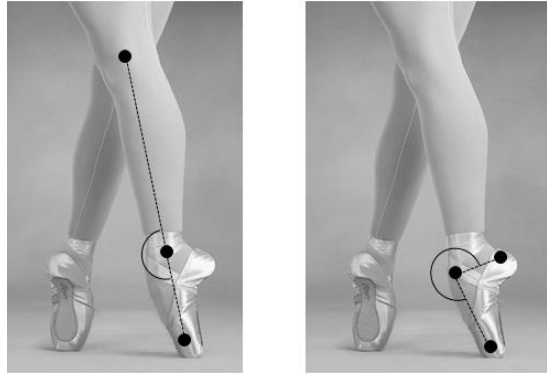


Figure 2. Definition of plantarflexion angle (left) and mid-foot flexion angle (right) en pointe.

One synchronized landing of the right foot on the force platform and pedobarograph was analysed from each of the three trials and an average was taken and compared between each condition (new and worn). Peak force was calculated at the instant of landing on the pedobarograph and force plate, respectively. Centre of pressure velocity was calculated by dividing centre of pressure displacement in the medio-lateral direction by the change in time over the ground contact phase.

2.4 Statistical analysis

To address the aim, a repeated measures MANOVA between conditions was performed, with peak vertical force, peak pressure, centre of pressure velocity, path length, plantarflexion and mid-foot flexion as dependent variables (IBM SPSS Statistics V.24). In case of significance, *post hoc* paired samples t-tests with bonferroni adjustment were performed on all dependent variables to locate differences between conditions.

3. Results

The main effect of condition on peak vertical force, centre of pressure velocity, plantarflexion and mid-foot flexion was significant ($F = 9.681$, $P = 0.002$). *Post-hoc* analyses revealed that

mid-foot flexion (New: $89.7 \pm 5.5^\circ$; Old: $96.1 \pm 3.9^\circ$) ($P = 0.002$, $\eta^2 = 0.516$) (Figure 3) and plantarflexion angles (New: $185.0 \pm 4.1^\circ$; Old: $188.2 \pm 5.0^\circ$) ($P < 0.001$, $\eta^2 = 0.646$) (Figure 4) were significantly greater in the worn pointe shoe compared to the new pointe shoe. There were no significant differences between worn and new pointe shoes for peak vertical force (New: 665 ± 59 N; Worn: 667 ± 60 N) ($P = 0.855$, $\eta^2 = 0.002$), and centre of pressure velocity (New: -0.10 ± 0.20 m/s; Worn: -0.17 ± 0.25 m/s) ($P = 0.404$, $\eta^2 = -0.17$).

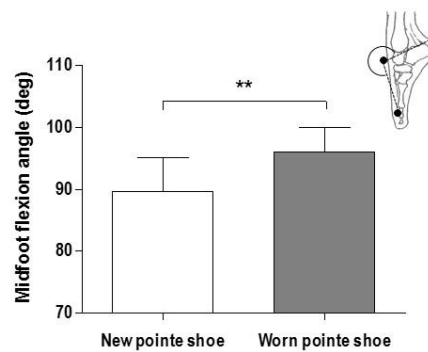


Figure 3. Mid-foot flexion in the new and well-worn shoe condition. Values are means \pm standard deviation. ** $p < 0.01$

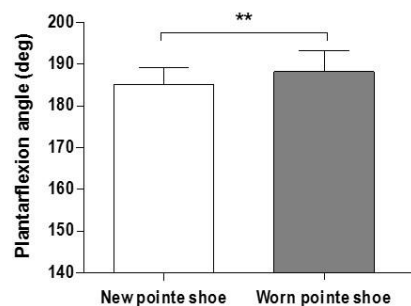


Figure 4. Plantarflexion in the new and well-worn shoe condition. Values are means \pm standard deviation. ** $p < 0.01$

4. Discussion

The purpose of this study was to investigate differences in foot and ankle kinetics and kinematics between new and worn pointe shoes. The results showed significantly greater mid-foot flexion and plantarflexion with the worn pointe shoe compared to the new pointe shoe. No differences were observed in peak vertical force or stability between the new and worn pointe shoe. The results of greater mid-foot flexion and plantarflexion in a worn pointe shoe is a novel finding and may be one contributing factor to the high incidence of ankle and foot injuries in female classic ballet dancers (Liederbach, Dilgen, & Rose, 2008; Nilsson, Leanderson, Wykman, & Strender, 2001; Garrick *et al.*, 1999). Greater mid-foot flexion in the worn pointe shoe appears to result from the metatarsals curling underneath the foot whilst en pointe (Russell, 2015), which may cause excessive stretching of the ligaments, which connect the metatarsal bones. This was accompanied by high levels of plantarflexion, comparable to those previously reported (173 degrees, Russell *et al.*, 2010b). In this position, the anterior talofibular ligament acts as the primary stabilizer of the lateral ankle, which places it at risk of injury due to high tensile forces and unfavorable strain length (Cawley & France, 1991; Bahr, Pena, Shine, Lew, & Engebretsen, 1998). These ligaments of the midfoot and ankle are not equipped to bear high loads or shear forces (Kadel, Boenisch, Teitz, & Trepman, 2005) and may be a risk factor for mid-foot and lateral ankle sprains, Lisfranc injury, cuboid subluxation or fractures in this population (Russell *et al.*, 2010a).

The finding that peak force was unaltered by pointe shoe condition offers support to the growing body of literature, which suggests that footwear characteristics do not alter peak ground reaction forces (Dixon, Collop, & Batt, 2000; Fu *et al.*, 2013). Although the shank of the pointe shoe becomes increasingly more compliant with hours of wear, the dissipation of ground reaction force on impact was not altered. This may be explained by the relatively

unaltered structural integrity of the toe box in the worn pointe shoe. The layers of paper, glue and fabric may deteriorate less with hours of wear than the material fabric of the shank. This also supports the results of stability measured via centre of pressure velocity. A relatively unaltered toe box, coupled with a locking of the subtalar joint may further explain why no differences in stability were found between pointe shoe conditions. For example, convergence and firm compression of the tibia, talus and calcaneus en pointe, locking the ankle in position (Kadel, 2006; Hamilton, 1982) may allow the dancer to maintain stability even as the integrity of the pointe shoe diminishes.

It should be acknowledged that this study assessed differences in worn pointe shoes compared to shoes that were new. It is common practice for dancers to “break in” their shoes prior to dancing to ensure comfort and the correct feel. The values we report for the new pointe shoe are likely to be less if assessed after dancers have customized the feel of the shoe. Therefore, investigating the time course of deterioration in the pointe shoe as well as the incidence of specific injuries in relation to pointe shoe deterioration would be an interesting direction for future research. In conclusion, this study provides some novel findings with respect to the kinematic changes that occur with new and worn pointe shoes. The worn shank of the pointe shoe results in greater levels of ankle plantarflexion and midfoot flexion than a new pointe shoe. Further research may show if this a risk factor for injury in ballet dancers. No changes in peak force or stability were found and this may be explained by a relatively unaltered toe box of the pointe shoe.

Declaration of interest: None

5. References

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