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Running title: Trunk dynamics in ballet dancers

ACCEPTED

ABSTRACT

Purpose Trunk control is essential in ballet and may be compromised in dancers with a history of low back pain (LBP) by associated changes in motor control. This study aimed to compare trunk mechanical properties between professional ballet dancers with and without a history of LBP. As a secondary aim we assessed whether asking dancers to use motor imagery to respond in a “fluid” manner could change the mechanical properties of the trunk, and whether this was possible for both groups.

Methods Trunk mechanical properties of stiffness and damping were estimated with a linear second order system, from trunk movement in response to perturbations, in professional ballet dancers with (n=22) and without (n=8) a history of LBP. The second order model adequately described trunk movement in response to the perturbations. Trials were performed with and without motor imagery to respond in a “fluid” manner to the perturbation.

Results Dancers with a history of LBP had lower damping than dancers without LBP during the standard condition ($P=0.002$) but had greater damping during the “fluid” condition ($P<0.001$) with values similar to dancers without LBP ($P=0.226$). Damping in dancers without LBP was similar between the conditions ($P>0.99$). Stiffness was not different between dancers with and without a history of LBP ($P=0.252$) but was less during the “fluid” condition than the standard condition ($P<0.001$).

Conclusion Although dancers with a history of LBP have less trunk damping than those without LBP, they have the capacity to modulate the trunk’s mechanical properties to match that of pain-free dancers by increasing damping with motor imagery. These observations have potential relevance for LBP recurrence and rehabilitation.

Keywords: spine; motor control; damping; stiffness; rehabilitation

INTRODUCTION

Classical ballet dancers have the ability to change the quality of their movement to portray a particular character, convey an emotion or meet the requirements of the choreographer, dance style or musical accompaniment. A key component is motor control of the trunk (2), which evolves in response to dance training and results in more accurate, efficient and repeatable movement patterns (30). For instance, in the execution of a *développé arabesque* (moving the gesture leg from the ground to an elevated position behind the body) differences in lumbo-pelvic control (kinematics) account for most of the variance between expert and less skilled dancers (2). On the basis of data from non-dancers (17, 39) it is reasonable to speculate that trunk control, including the ability to regulate movement quality, might be modified in ballet dancers with a history of low back pain (LBP).

Changes in the recruitment of trunk muscles have been reported in association with LBP and this has implications for control of the spine (16). Electromyography (EMG) recordings of the trunk muscles commonly reveal a pattern of compromised activity of the deeper trunk muscles including multifidus (22) and transversus abdominis (17) and augmented activity of the larger, more superficial trunk muscles such as obliquus externus abdominis (32). Consistent with EMG findings, measurement of deep trunk muscle morphology using magnetic resonance imaging has demonstrated that LBP in dancers is associated with smaller cross sectional area of the multifidus muscles (13) and reduced shortening with contraction of the transversus abdominis muscles (12). It has been hypothesized that altered recruitment and morphology of trunk muscles underlies changes in the mechanical behavior of the trunk in people with recurring episodes of LBP (15). However, whether trunk mechanical behavior is altered in ballet dancers with a history of LBP is unknown.

Although movement quality incorporates many components, viewed simply, the dynamic behavior of the trunk depends on its inertia, damping and stiffness properties (11, 27). Estimation of trunk mechanical properties from the response to small perturbations may yield information about trunk control in ballet dancers with and without a history of LBP. Stiffness (Nm^{-1}) is the resistance to trunk displacement (28) and is dependent on muscle activity (e.g. co-contraction) and passive constraints (3, 28). Damping is the resistance to trunk velocity (Nsm^{-1}) (1) and prevents unwanted oscillations in a system. As damping smooths movement at higher frequencies, change in damping has the potential to affect the quality of trunk movement, which could be an important feature in dance. Estimation of the dynamic properties of the trunk has identified greater stiffness and less damping in people with recurrent LBP than pain-free individuals (15). Trunk dynamics have not been studied in dancers.

Evaluating the change in mechanical behavior of the trunk in different conditions may provide insight into how dancers modulate movement quality. Dance training frequently employs mental practice including motor imagery, as a technique to change both qualitative and quantitative aspects of movement performance (8, 9, 35). For example, when using motor imagery, professional dancers can improve the quality of a dance-specific movement sequence by changing muscle activity level (9) and kinematics (8). Kinesthetic motor imagery simulates the “felt” experience of performing movement (8) and produces similar cortical activation to actual movement (19). Whether dancers can change basic mechanical properties of the trunk with motor imagery, and whether this can also be achieved by dancers with a history of LBP remains unclear. For the current study, a standard and a “fluid” motor image were developed in conjunction with dance experts to evoke movement responses with different qualities that would be likely to influence the properties of stiffness and damping.

This study had two aims. The first aim was to determine whether dynamic properties of the trunk (i.e. stiffness and damping), as estimated from responses to small perturbations applied to the trunk; differ between dancers with and without a history of LBP. The second aim was to investigate whether these properties could be modified by motor imagery. This was achieved by comparison of the mechanical responses to perturbations with a standard instruction with the responses when dancers employed the motor image of using their body in a “fluid” manner. We hypothesized that dancers with a history of LBP would have less damping and greater stiffness of the trunk than those without pain, and a reduced ability to modulate these properties in the “fluid” condition.

MATERIALS AND METHODS

Participants

Thirty professional classical ballet dancers with and without a history of LBP (11 male, 19 female, mean (SD): 24 (4) years, 172 (10) cm, 60 (13) kg) volunteered for this study. Participants were recruited from a group of dancers on full workloads (n=49) who were on tour with The Australian Ballet. Dancers of all ranks were included and the participants’ dancing experience ranged from 7-28 years, of which 1-13 years was professional. Participants were excluded if they presented with LBP at the time of testing or LBP of a non-musculoskeletal etiology, spinal trauma or surgery, major postural abnormality (e.g. severe scoliosis), neurological or respiratory disorders or pregnancy in the preceding 2 years.

Dancers were categorised into either no LBP or LBP groups on the basis of interview with the dancer and the dance company’s physiotherapists. Dancers were included in the LBP group if they reported a history of pain in the low back/pelvic area that required treatment or

modification of class, rehearsal or performance. Dancers were not excluded if they also reported pelvic/hip region pain. Of the 30 dancers, 22 dancers reported pain in the lower back or pelvic/hip region. Fourteen dancers reported back pain (pain between the lower ribs and gluteal fold) within the preceding 6 months and 8 dancers reported pain prior to that (range 0.5-13y). Nine of these dancers also reported pelvic/hip region pain (pain from the top of the pelvis to upper thigh) within the preceding 6 months. To gauge self-reported disability, the LBP group completed the Roland-Morris questionnaire, (Scoring range 0-24 - (mean (SD) 1(2)) and the Oswestry Disability Index (version 2.0)(Scoring range 0-100% - (8(9)%)). They also recorded their LBP level over the previous 6 months, on a 10cm Visual Analogue Scale anchored with 0 'no pain' and at 10 'worse possible pain imaginable' (mean(SD): 3(3) out of 10). There was no difference between groups for age, height, weight and years of dancing (t-test for independent samples: all $P>0.07$). Procedures were approved by the institutional Medical Research Ethics Committee and were undertaken according to the Declaration of Helsinki. Participants provided written informed consent prior to participation.

Experimental Procedure

Participants sat in a semi-seated upright position with their arms held relaxed by their sides and their head maintained in a neutral position (Fig. 1). The pelvis was fixated with a belt to minimize movement. A harness was tightly fitted around the thorax for attachment of cables at the front and back at the level of the 9th thoracic vertebrae, the approximate location of the trunk's centre of mass (15, 32). The cables passed over low friction pulleys to weights (7.5 % body weight) attached by an electromagnet. As the front and back weights were equal, minimal muscle activity was required to hold the trunk upright. Force transducers (Futech, LSB300, USA,

Irvine, CA) were placed in series with the cable between the weights and the trunk to measure the force applied to the trunk. Either the front or back weight was released at random by switching off the electromagnet at unpredictable times to induce a trunk perturbation. After each perturbation the weight was reattached after ~5s. Force data were collected at 2000 samples/s using a Micro1401 data acquisition system (Cambridge Electronic Design Limited, UK) and Spike 2.6 software (Cambridge Electronic Design, Limited UK).

Participants were tested under 2 conditions. The aim was to use verbal cues to create a motor image to elicit a different movement response in each condition. The instructions for these conditions were devised in conjunction with dance experts. Instruction given for the standard condition was; “think of yourself sitting upright in a relaxed manner then respond as if you are sitting on a bus and the driver hits the brakes when you are not expecting it and you right yourself as quickly as possible.” This condition was repeated for 21 front and 21 back weight drops, in random order. Instruction for the second condition aimed to elicit a “fluid” response. It was; “think of yourself as fluid in your movements and respond in a fluid manner; think of holding yourself in a gentle lifted way by sustaining yourself through a gentle humming inside your body.” This condition was repeated for 5 front and 10 back weight drops in random order. The number of repetitions was less for the front weight drops as these were initially only included so the participant could not predict the direction of the perturbation, however, we subsequently elected to include these trials in the analysis. The standard condition was always performed first and not randomized as it was considered that the training of the “fluid” imagery condition could modify the movement response and carry over to the standard condition if it was performed second.

Data analysis (Modeling procedures and analyses)

Force data were analyzed offline in Matlab (Mathworks, U.S.A., Natick, MA). Trunk parameters were assumed to be constant over time and were estimated with a second order linear model for each perturbation.

$$F = m\ddot{x} + B\dot{x} + Kx \quad (1)$$

F (N) is the resultant force acting on the trunk ($F_{\text{front}} - F_{\text{back}}$), m (kg) the trunk mass, B (Nsm^{-1}) trunk damping, and K (Nm^{-1}) the trunk stiffness. Trunk linear displacement, velocity and acceleration are represented by x, \dot{x}, \ddot{x} respectively, and were calculated from the force transducer attached to the weight that remained attached during a perturbation (i.e. opposite side to the released weight). The cable attached to the weight and the force transducer remained tensioned during the perturbations, as participants did not accelerate more than gravitational acceleration. As the perturbation weight and force were known (7.5% of body weight) trunk acceleration was determined by dividing the force by the mass. Trunk velocity and displacement were derived by numerically integrating acceleration once and twice over time, respectively. To increase robustness of the estimation of the trunk parameters, both sides of equation 1 were integrated twice over time (38). As the participants did not move at the time of the weight drop, initial values of displacement and velocity for the integration procedure were set to zero.

$$\int_{t_0}^{t_1} \int_{t_0}^{t_1} F dt = mx + B \int_{t_0}^{t_1} x dt + K \int_{t_0}^{t_1} \int_{t_0}^{t_1} x dt dt \quad (2)$$

The moment the weight dropped was t_0 and t_1 was 0.329 s later. The time duration of the model was held constant between conditions and between participants to avoid bias of the estimated trunk parameters related to differences in model duration between conditions (1) and was set to 0.329 s. This duration reflected the common mode of all trials across all participants. The unknown variables of the trunk m, B and K were estimated by minimizing the least squares

differences between the trunk displacement derived from the second order linear model and the actual trunk displacement. The R^2 between the measured trunk displacement and the modeled trunk displacement was calculated. Trunk parameter estimates that explained more than 97% variance of the measured trunk displacement were accepted. In total, 2.4% of all trials were discarded. The amount of trunk displacement was assessed at $t=0.329$ s.

Statistical analysis

Statistics were performed with Stata (v12, StataCorp LP, USA, TX). Outcome variables (trunk m , B , K) were averaged across the forward and backward perturbations within each condition (standard and “fluid”). A repeated measures analysis of variance (ANOVA) was performed for each of the outcome variables (m , B , K , trunk displacement) to detect whether there were any differences between the groups, conditions and perturbation direction. Group was entered as a between subjects factor (2 levels: no LBP and LBP dancers) and Condition (2 levels: standard and “fluid” responses) and Direction (2 levels: forward and backward perturbations) were entered as repeated within subjects factors. Stiffness values did not pass the Shapiro-Wilk test for normality and were log transformed. When significant interaction was identified related to group, post-hoc comparisons were undertaken with Bonferroni correction for multiple comparisons to evaluate group differences. Because of the smaller number of front weight drop (backward perturbation) trials we undertook an additional analysis with data from the first five repetitions in each direction. This did not change the outcome with respect to differences between direction and the original analysis was included. The corrected P -values are reported. Significance was set to $P<0.05$.

RESULTS

Dancers with a history of LBP had significantly lower damping than dancers without LBP for perturbations applied in the standard condition (Interaction - Group \times Condition; $F=4.97$, $P=0.03$, post-hoc; $P=0.002$) (Fig. 2). Although damping was greater in the “fluid” condition than the standard condition for the dancers with a history of LBP (post-hoc; $P<0.001$), this was not the case for the dancers without LBP (post-hoc; $P>0.99$). In the “fluid” condition there was no difference in damping between groups (post-hoc; $P=0.226$). Dancers with and without a history of LBP had greater damping when perturbed backwards than when perturbed forwards (Main effect - Direction; $F=7.29$, $P=0.012$).

Trunk stiffness was not significantly different between the groups (Main effect - $F=1.37$, $P=0.252$). Stiffness was less for perturbations applied in the “fluid” condition than in the standard condition (Main effect - $F=23.69$, $P<0.001$). Stiffness was higher when perturbed backwards than when perturbed forwards (Main effect - $F=4.51$, $P=0.043$) (Fig.3).

Trunk displacement was greater when perturbed forwards than when perturbed backwards (Main effect - $F=14.69$, $P=0.001$)(Table 1). Trunk displacement was also greater in the “fluid” condition than in the standard condition (Main effect - $F=18.46$, $P<0.001$). No significant difference between groups was identified for displacement (Main effect - $F=0.09$, $P=0.768$) or the estimated trunk mass (Main effect - $F = 0.00$, $P=0.977$). Estimated trunk mass was higher during the forwards than backwards perturbations (Main effect - $F=26.53$, $P<0.001$), and was higher during the standard condition than the “fluid” condition (Main effect - $F=12.25$, $P=0.002$). Differences in estimated trunk mass are most likely explained by differences in the effective mass that was perturbed as a result of changes in trunk stiffness and damping properties.

DISCUSSION

The first aim of this study was to determine whether trunk damping and stiffness differ between dancers with and without a history of LBP. The secondary aim was to assess how trunk stiffness and damping change when motor imagery is used to evoke a “fluid” movement response to the perturbation, and whether the ability to adapt differs between dancers with and without a history of LBP. **We showed that dancers with a history of LBP had lower trunk damping in the standard condition, but were able to increase damping by using motor imagery to respond in a “fluid” manner to attain values comparable to dancers without LBP,** whereas dancers without LBP had similar values of damping in the standard and “fluid” conditions.

Trunk damping, but not stiffness is modified in dancers with a history of LBP

Reduced damping in dancers with a history of LBP in the standard condition implies a compromised ability to attenuate velocity of trunk movement after a perturbation. This finding agrees with lower damping found in non-dancers with recurrent LBP (15) and partially confirms our hypothesis. **A well-damped system returns to equilibrium rapidly when perturbed,** whereas a less damped system will oscillate for a longer duration. Damping smooths movements at higher frequencies and could augment quality of trunk movement. **It is probable that higher damping observed in pain-free individuals reflects more optimal motor control.** It follows that lower damping in dancers with a history of LBP may be caused by compromised ability of the nervous system to respond to perturbation. This could be mediated by compromised sensory or motor function or both, which would affect mechanisms such as reflex control (18).

The deep paraspinal muscles play an important role in the control of spine motion (20, 40) and may contribute to compromised damping (34). From a sensory perspective, changes in

muscle spindle function could contribute (34) to altered trunk damping. These receptors respond to changes in length of muscles, such as that induced by changes in relative orientation of body parts/vertebra (6) and are normally found in high density in the deep paraspinal muscles including multifidus (31). From a motor perspective, the multifidus muscles play an important role in fine-tuned control of spine segments (23, 29). Further, proprioceptive acuity is enhanced by gentle to moderate (but not intense) muscle contraction (37). Changes in the ability of the multifidus muscles to provide sensory input or generate a motor response could have consequences for damping. LBP has been associated with impaired proprioception in non-dancers (4) and this is related to distorted input from the multifidus muscles (5). Multifidus muscle activity is reduced (36) and delayed (21) in non-dancers, and cross sectional area is reduced in dancers with LBP (13). Together, these changes could underpin less optimal damping in dancers with a history of LBP. Lower damping may also reflect change in passive structures as a result of injury or a combination of compromised function of both active and passive restraints to movement. Further research is required to clarify the relative contribution of these mechanisms.

In contrast to other studies (10, 15) and our hypothesis, trunk stiffness was not significantly higher in dancers with a history of LBP than dancers without LBP. Increased stiffness is thought to reflect the augmented activity of superficial trunk muscles (3, 28), which is commonly reported in association with LBP (7, 39) and may be a strategy to protect the spine from pain and injury (16, 39). Support for this proposal comes from modelling studies, which have identified that contraction of superficial trunk muscles increases spinal stability (7, 39). Although commonly adopted in non-dancers, augmented activity of superficial trunk muscles may not be a useful strategy for dancers with LBP as the accompanying increase in trunk

stiffness may be incongruent with their required function. For instance, increased stiffness may have a negative impact on quality of movement and hence performance. This is because increased stiffness could reduce spine movement (26), increase spinal load (24), and compromise balance control as a result of reduced potential for the spine to contribute to balance reactions (25, 33). The severity of pain and level of dysfunction may also influence the muscle strategy used by dancers with LBP. As the dancers with a history of LBP were on full workloads and reported low levels of disability, this may have limited our participant recruitment to dancers who had only minor adaptation.

Dancers without LBP had comparable values for damping in both the standard and “fluid” motor imagery conditions and less stiffness during the “fluid” condition. It is unclear why these dancers did not alter damping between the two different conditions. One interpretation is that damping was already optimal in this regard, in the standard condition, and further modification would have provided no additional benefit. Alternatively, the absence of significant effect may be secondary to the statistical issue of the small sample size of pain-free dancers (see below).

Dancers with a history of LBP can use imagery to modify trunk mechanical properties

Although dancers with a history of LBP had less damping than pain-free dancers during the standard condition, when they were instructed to use motor imagery to evoke a “fluid” response to the perturbation, they demonstrated the capacity to modulate the mechanical properties of their response by increasing trunk damping to values similar to dancers without LBP. This contrasts our hypothesis that dancers with a history of LBP would have reduced ability to adapt the mechanical properties of the trunk. This observation has two implications.

First, this implies that dancers were either able to improve/tune the natural strategies that modulate damping (e.g. reflex control), or find a solution to compensate for the compromised control of this mechanical property (see below). Regardless of the underlying mechanism, dancers with a history of LBP were able to change the quality of the movement response to make it more “fluid” in nature and more effectively absorb energy (the outcome of improved damping) with the benefit of “smoother” movement. Second, **this observation implies that dancers with a history of LBP have the potential to improve the quality of trunk control and it may be possible to draw on this potential for rehabilitation.**

Although the exact neural mechanisms by which motor imagery changes performance are not fully established, there is evidence that mental rehearsal can increase (14) or decrease the amplitude of H-reflexes (the electrical equivalent of a spinal stretch reflex) and is associated with cortical activation that is similar to that when movements are actually produced (19). In professional ballet dancers, motor imagery has been observed to increase hamstring muscle activation (9) and peak external hip rotation (8) resulting in more optimal dynamic alignment during a demi-plié and sauté (a dance specific movement sequence involving bilateral knee flexion followed by a jump). **In addition to changing muscle activation and kinematics with motor imagery, here we show that dancers with a history of LBP can also modify mechanical properties of the trunk. Whether other clinical groups can achieve similar benefit with motor imagery requires investigation.**

Methodological considerations

There are several methodological issues that warrant discussion. Motion of the pelvis and lower limb was restricted in this paradigm and the study focussed on control of the trunk (movement between the pelvis and thorax). This enabled precise estimation of the mechanical properties of this region, without the confounder of variation in strategy of hip and pelvic control. Future work should build on this data with inclusion of the lower limbs. Trunk stiffness and damping were assumed to remain constant over time and the duration was standardised. This assumption is a simplification of actual trunk control, which changes over time, however simplification is necessary to enable the estimation of trunk parameters. The validity of our estimates is strengthened by the observation that linear values of stiffness and damping were able to model actual measured trunk movement. Models that explained less than 97% of the variance of the measured trunk displacement were excluded from further analysis. This study used a convenience sample of elite classical ballet dancers and the high prevalence of LBP in professional ballet dancers limited the available sample size of pain-free dancers. This limited the statistical power of that group.

Conclusion

Dancers with a history of LBP have reduced damping when the trunk is perturbed in a standard condition and this may impact on performance. The increase in damping with “fluid” motor imagery demonstrates that dancers with a history of LBP can change this mechanical property and this could have implications for rehabilitation. However, whether there is potential to induce long-term improvement and whether this has benefit for management of LBP or improved performance requires further consideration.

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Conflict of Interest

The authors have read and concur with the content in this manuscript. We declare that we have no financial or personal relationships that can inappropriately influence our work. The results of the present study do not constitute endorsement by ACSM.

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ACCEPTED

Figure Legend

Fig. 1 Methods. Participants sat in a semi-seated position with the pelvis fixated. Equal weights were attached to front and back so that no force acted on the trunk and minimal trunk muscle activity was required to maintain an upright posture. The weight was released from one side of the trunk by release of an electromagnet. Force transducers placed in series with the cable measured the force applied to the trunk.

Fig. 2 Trunk damping (mean + SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP), estimated from backward and forward trunk perturbations in the standard and “fluid” conditions. * - $P < 0.05$ for comparison between LBP and No LBP groups; # - $P < 0.05$ for comparison between conditions for the LBP group. The main effect for direction was significant.

Fig. 3 Trunk stiffness (mean + SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP), estimated from backward and forward trunk perturbations in the standard and “fluid” conditions. * - $P < 0.05$ for comparison between conditions for both groups. The main effect for direction was significant.

Figure 1

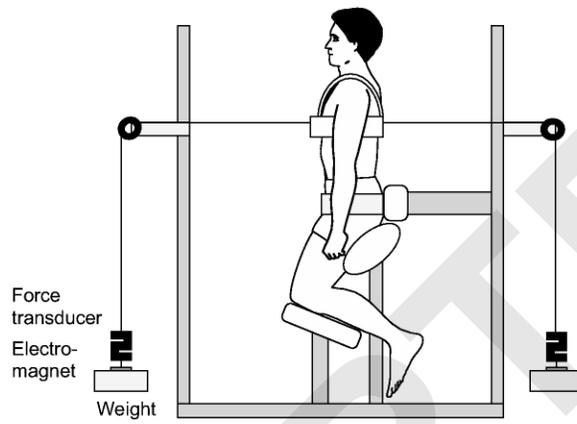


Figure 2

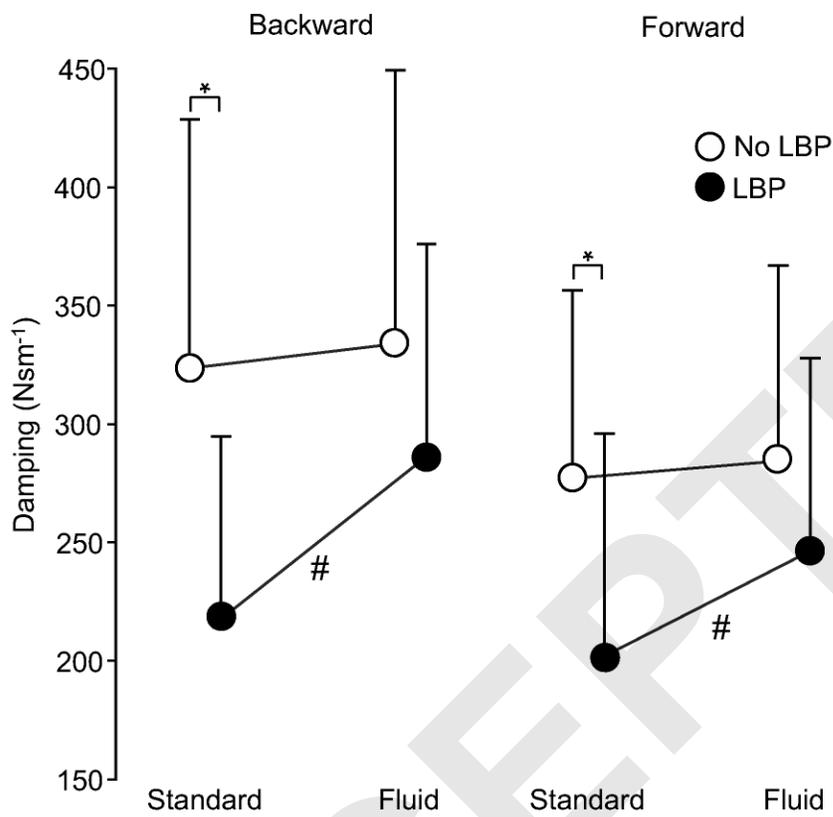


Figure 3

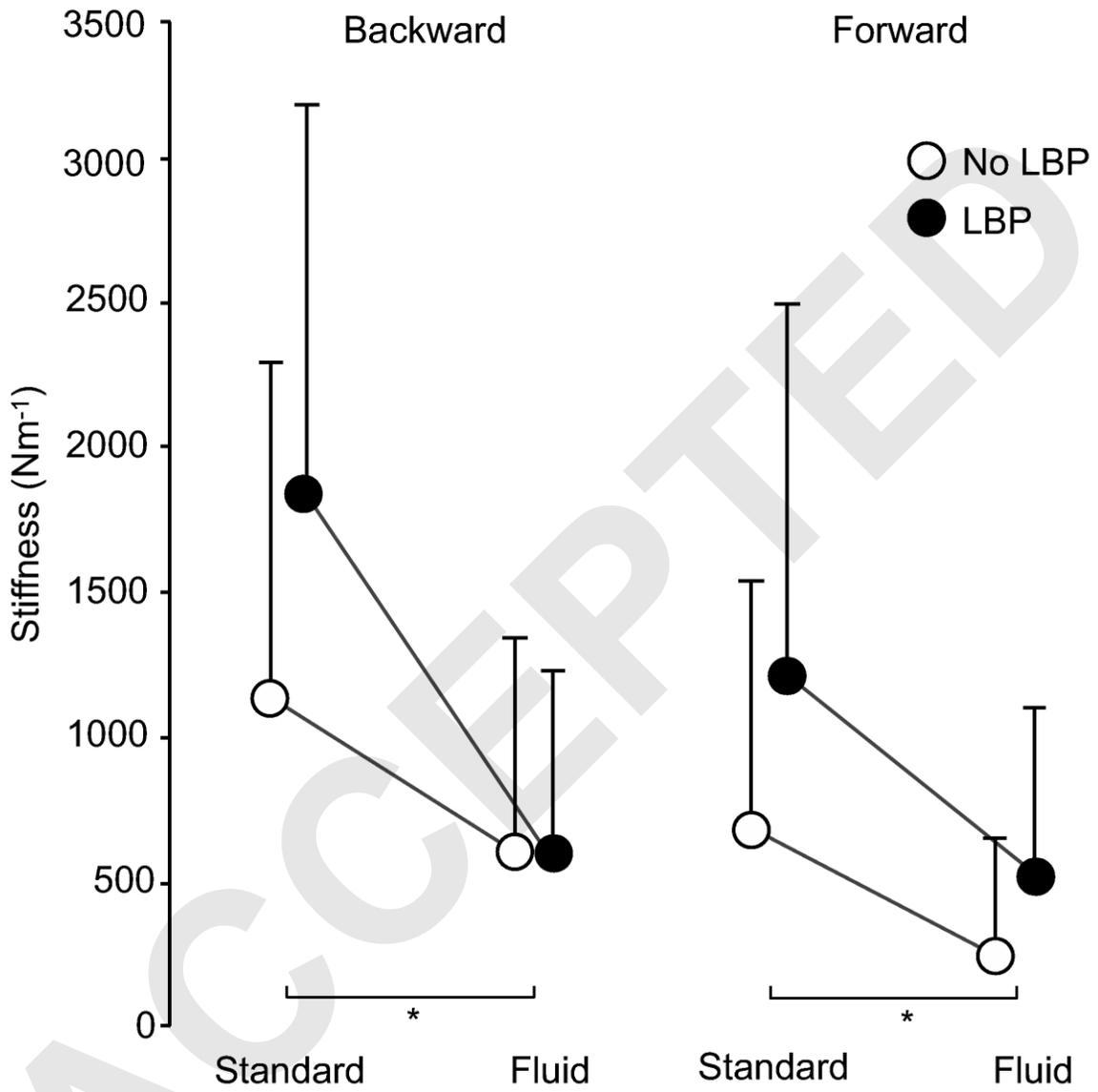


Table 1. Estimated trunk mass and trunk displacement.

Standard Condition				
	Forward		Backward	
Trunk	No LBP	LBP	No LBP	LBP
Estimated mass (kg)	21.5(4.9)	22.3(6.9)	19.0(6.3)	19.2(6.6)
Displacement (cm)	3.1(0.8)	3.0(0.6)	-2.7(0.9)	-2.6(0.7)

Fluid condition				
	Forward		Backward	
Trunk	No LBP	LBP	No LBP	LBP
Estimated mass (kg)	20.6(5.7)	21.0(6.6)	18.3(6.5)	17.3(6.0)
Displacement (cm)	3.4(0.7)	3.2 (0.5)	-3.0(0.8)	-3.1(0.8)

Data are reported as mean(SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP) estimated from forward and backward trunk perturbations in the standard and “fluid” conditions.