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Full Length Article

Regulation of hip joint kinetics for increasing angular momentum during the initiation of a *pirouette en dehors* in classical ballet

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ABSTRACT

This study examined how dancers regulate the hip joint kinetics to coordinate the upper and lower body angular momenta with the increased rotation of *pirouette en dehors (pirouette)* during the preparation. During the preparation of the *pirouette,* the upper body rotates greatly about the vertical axis; however, the lower extremity remains relatively stationary. Therefore, there must be specific control at the hip to coordinate the upper and lower body angular momenta in turns of increased rotation. Kinematics and kinetics of single to quadruple *pirouettes* performed by eight ballet dancers were analysed using a motion capture system and force plates. Peak angular momentum of the upper body around the vertical axis increased from the single to the quadruple *pirouettes*. The vertical components of hip abductor torque of the anterior lower limb and hip adductor and flexor torques of the posterior lower limb contributed to generating the clockwise moment acting on the upper body around the vertical axis, which was reduced by the vertical components of the hip internal and external rotator torques. Thigh flexion angles of the posterior and anterior lower limbs, respectively, at the peak adductor and abductor torques at the corresponding hip joints changed with the number of revolutions and changed the percent contribution of the relevant hip joint torques about the vertical axis. The results suggest that dancers need to regulate hip joint torques along with the thigh angles in the *pirouettes* depending on the number of revolutions.

1. Introduction

In the whole body rotation such as pedestrian turns or dance turns, performers generate the necessary angular momentum of the whole body around the vertical axis by exerting forces and free moments on the ground. In order to effectively exert forces and free moments on the ground, performers need to generate lower limb joint torques, which would transmit the ground reaction forces to the trunk and enable the upper body to rotate around the vertical axis. The hip joint torques and forces together with ground reaction forces determine the rate of change in the angular momentum of each limb. The reaction of the hip joint torques and forces determine the rate of change in the angular momentum of the upper body. Therefore, investigating the hip joint kinetics during a whole body rotation is useful for better understanding of how the vertical angular momenta of the upper and lower body are coordinated. In the *Fouetté* turn, the magnitude of the component of the hip joint torque of the supporting leg around the vertical axis must be less than the magnitude of the maximum frictional torque from the floor; otherwise, the supporting leg would rotate around the vertical axis in the opposite direction to that of the upper body (Imura & Yeadon, 2010). In the step turn during walking, the gluteus medius of the

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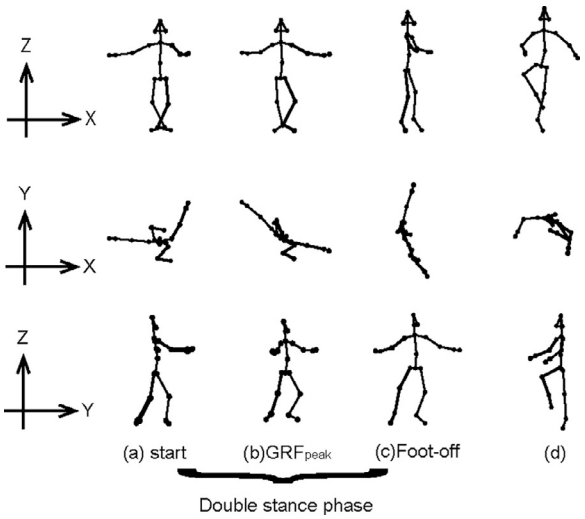

Fig. 1. Stick pictures of the clockwise *pirouette en dehors*. Upper: Front view; Middle: Top view; Lower: Side view. (a) start: the total external moment around the vertical axis passing through the mass centre of the whole body starts to act on the feet clockwise; (b) GRF_{peak}: The vertical GRF peaks when the right (posterior) lower limb pushes the floor; (c) foot-off: the right foot comes off the floor; (d) the left (anterior) lower limb stands on the tiptoe. At this time, the second revolution already begins. The thick lines represent the right upper and lower limbs.

supporting limb is activated to exert the hip abductor torque for the initial rotation of the pelvis during the stance phase of the limb (Hase & Stein, 1999). The hip external rotator torque of the limb is reduced compared to straight gait as the pelvis rotates in the turn direction to control the position of the limb relative to the pelvis (Dixon, Stebbins, Theologis, & Zavatsky, 2014). These previous studies have shown a possible role of hip joint kinetics to coordinate generation of the angular momenta of the upper body and lower limbs. Examining the knee and ankle joint torques is also helpful to consider the propagation of the ground reaction force through the ankle and knee joints to the pelvis combined with foot, shank, and thigh dynamics.

Pirouette en dehors performed with different numbers of revolution provides a good opportunity to understand how performers coordinate the angular momenta of the upper body and lower limbs by exerting the hip joint kinetics to satisfy the increasing demand for the vertical angular momentum. In a clockwise *pirouette en dehors* (when viewed from above, a turn to the right), dancers rotate the upper limbs substantially clockwise followed by the pelvis against the feet during the initial double stance phase (Fig. 1a and b). Dancers translate the whole body mass centre towards the anterior lower (left) limb while being subjected to a medially directed ground reaction force on both lower limbs with the externally rotated position (Fig. 1b and c) (Kim et al., 2014a; Lin, Chen, Su, Wu, & Lin, 2014; Zaferiou, Flashner, Wilcox, & Mcnitt-Gray, 2017; Zaferiou, Wilcox, & McNitt-Gray, 2016). In the following single stance phase, the whole body turns on the left lower limb using the clockwise angular momentum gained by the upper limb rotation during the double stance phase (Fig. 1d and e) (Kim et al., 2014). In light of the result that the whole body angular momentum increased without significant change in the duration of the double stance phase (Kim et al., 2014), the lower limb joint torque is expected to be exerted more as the number of revolutions increased. However, no studies have clarified how the lower limb kinetics, especially the hip joint kinetics are regulated to coordinate the angular momenta of the upper body and lower limbs during *pirouettes en dehors*.

To what degree each hip anatomical joint torque component has the vertical component depends on the orientation of the hip joint (Iino, Fukushima, & Kojima, 2014). For example, because the rear hip joint is in an abducted and flexed position, the hip extensor and abductor torques contribute to the moment acting on the pelvis around its vertical axis in tennis strokes and softball batting (Akutagawa & Kojima, 2005; Iino & Kojima, 2001; Iino & Kojima, 2003; Iino et al., 2014). In a single clockwise *pirouette en dehors*, the hip abductor and extensor torques of the anterior (left) lower limb and hip abductor and flexor torques of the posterior (right) lower limbs are exerted in the hip abducted, flexed, and externally rotated position (Zaferiou et al., 2017). These previous studies have not investigated how performers regulate the hip joint kinetics and joint angles when they must increase the resultant moment acting on the pelvis around the vertical axis. For the demand of increasing the vertical angular momentum in *pirouette en dehors*, dancers may not only increase the magnitudes of exerted torques but also change the hip joint angles.

An important question to resolve is how dancers regulate hip joint torques and angles according to the number of revolutions to be performed during the double stance phase of the *pirouette en dehors*. The purpose of our study was to investigate how advanced dancers regulate the hip joint torques during the initial double stance phase of the *pirouette en dehors*, depending on the number of revolutions performed. Our hypothesis about the clockwise *pirouette en dehors* during the double stance phase was as follows: advanced dancers would regulate the hip joint torques around anatomical axes along with the thigh angles relative to the upper body depending on the number of revolutions.