HIP JOINT KINETIS CONTRIBUTING TO UPPER BODY TWISTING DURING *PIRUETTÉ* EN DEHOR IN CLASSICAL BALLET

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The aim of this study was to investigate the hip joint kinetics contributing to the upper body rotation during the initial phase of *pirouetté en dehor* in classical ballet. The hypotheses were that the contributions of the hip joint kinetics would change depending on the phases and numbers of rotations. *Piruettés en dehor* from single to quadruple revolutions were captured and analysed by the inverse dynamics method. The hip abductor torque of the anterior leg, the hip flexor and adductor torques of the posterior leg contributed to the rotation (90-130%, 36-47% and 26-36%, respectively) during a double stance phase. These increased with every number of revolutions. The hip internal rotator torque of the anterior leg and moment of the anteroposterior hip joint reaction force of the posterior leg limited the rotation during the double and the following single stance phase.
KEY WORDS: turn, trunk rotation, hip joint kinetics, ballet.

INTRODUCTION: As one of the aesthetics of an outward whole body rotation around a vertical axis on single leg in ballet (*pirouetté en dehors*), dancers are required to perform *pirouetté en dehors* with a larger rotational speed (Torrant et al., 2008). To perform clockwise *pirouetté en dehors* using the left lower limb as the supporting leg, a dancer prepares in a double stance with the right (leading) arm extended in front of the chest and the left (trail) arm along the shoulder line (Figure 1(a)). Then the dancer horizontally rotates the upper body clockwise with both feet on the floor (Figure 1(b)). Finally, the dancer turns on the anterior leg (supporting leg) (Figure 1(d)-(e)). To facilitate the subsequent rotations of the whole body, the larger rotation of the pelvis would be better as the numbers of revolutions increases. The upper body rotation is promoted by the increase of the upper limb angular momentum through the trunk twisting during initiation of *pirouetté en dehors* (Kim et al., 2014). The generation of the angular momentum of the whole body differs depending on the lower limb motions (Zaferiou et al., 2016). Thus, generation of the upper body angular momentum would change due to the different hip joint kinetics for flexion-extension of both lower limbs (Phase1 (Double stance): from the Start to the Foot-off) and for translation of the body (Phase 2 (Single stance): from the Foot-off to the ALK). Contributions of the anatomical components of the hip joint kinetics for the upper body rotation would be different depending on the phases. The purpose of this study was to investigate the hip joint kinetics contributing to the upper body rotation during the initiation of *pirouetté en dehors*. The hypotheses were that: The twisting angle of the upper body would change depending on the phases and number of revolutions; the contributions of the torques and moments of the reaction forces of both hip joints would change depending on the phases and numbers of revolutions.

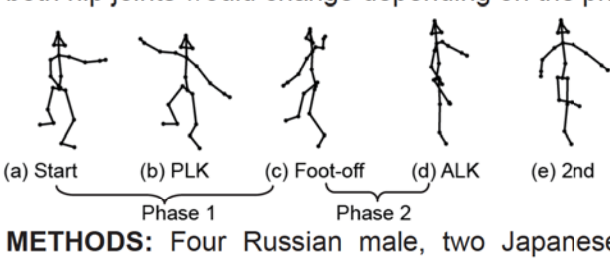

Figure 1 Stick pictures of the *pirouetté en dehors*. (a) Start: the angular momentum around the whole body centre of mass (CoM) turns to be clockwise; (b) PLK: Vertical GRF of the posterior leg is maximum; (c) Foot-off: The posterior foot takes off from the floor; (d) ALK: Vertical GRF of the anterior leg is maximum. At this point, the first revolution already begins; (e) 2nd: the start of the second revolutions.

METHODS: Four Russian male, two Japanese male, and two Japanese female ballet dancers (Height: 1.72 ± 0.06 m; mass 58.2 ± 9.44 kg; year 26.1 ± 9.46 yr) performed clockwise *pirouetté en dehors* with from single to quadruple revolutions per one kick. The experimental procedure was approved by the local ethics committee, and written informed consent was obtained from all dancers before the experiment. The performances were recorded using eight VICON MX cameras at a frame rate of 250 Hz. The ground reaction forces acting on feet were recorded at 1000 Hz simultaneously with the cameras.

The one revolution of each dancer's best turn was analysed using inverse dynamics method by Hof (1992). The inertial properties of the dancers were referred to Ae et al. (1992) for Japanese and de Leva (1996) for Russian. The twisting angle was determined using the markers on the pelvis. Using the longitudinal axes of the thighs and lower legs, the hip joint coordinate system was defined. Each anatomical component of the hip joint torques was determined by projecting them to the hip joint coordinate system. Moments of the hip joint reaction forces were determined around a CoM of the upper body. Then each torque component and the moments were projected to the vertical axis passing through the CoM. Two-way, repeated measures of ANOVA was performed to test the effects of the numbers of rotations and differences of the components, keeping the significance level below 0.05 using Bonferroni correction in post hoc analyses.

RESULTS: The twisting angle of the upper body changed depending on the phases and number of revolutions. The upper body rotated more in the phase 2 than in the phase 1 in all the numbers of revolutions (Figure 2). The twisting angle in the phase 1 increased with the number of revolutions (Figure 2). The twisting torque was corresponded to the rate of change of the angular momentum (Figure 4 (a)). The rate of change of the angular momentum of the upper body turned negative to positive before the Foot-off (Figure 4 (a)).

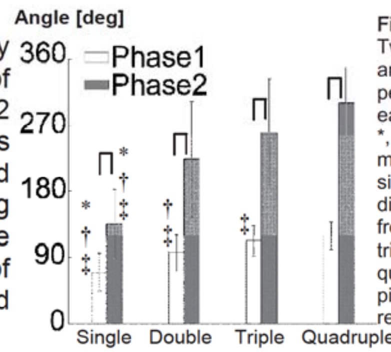

Figure 2 Twisted angle of pelvis during each phase. *, †, and ‡ mean significantly different from double , triple, and quadruple pirouette respectively.

The joint motions were more dynamical in the phase 2 than in the phase 1 despite the smaller torques compared to the phase 1. In the phase 1, the hip joint of the posterior leg flexed and internally rotated at the start then externally rotated, adducted, and flexed, exerting the external rotator, adductor, and flexor torques (Figure 3 (a)(b)). The hip joint of the anterior leg flexed and abducted until the PLK and then extended, adducted, and internally rotated, exerting the hip adductor, extensor, and internal rotator torques (Figure 3 (d)(e)). The posterior and lateral forces of both hip joints changed to the medial after the PLK (Figure 3 (c)(f)). The knee and ankle joints of the posterior and anterior legs flexed and dorsiflexed (data not shown). In the phase 2, the motions became greater despite the smaller torques than before (Figure 3 (a)(b)). The hip joint force of the posterior leg acted the thigh to the right and posteriorly (Figure 3 (c)(d)). The hip joint force of the anterior leg acted the thigh to the left in the quadruple turn while it acted to the right until the ALK in the single turn (Figure 3 (c)). The anterior force acted to the thigh during the phase 2 (Figure 3 (f)). The knee and ankle joints of the posterior and anterior legs extended and plantar flexed (data not shown).

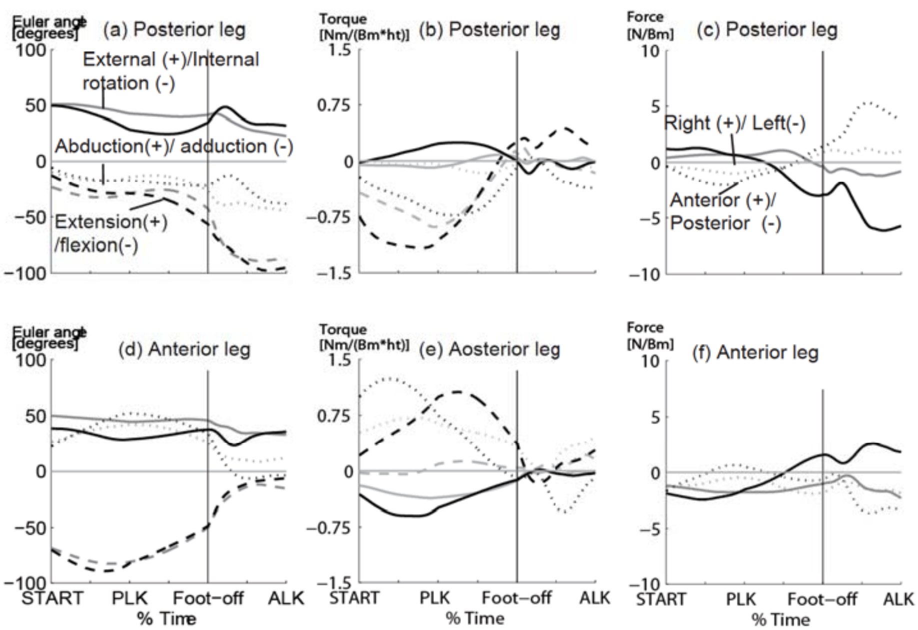

Figure 3 Euler angles ((a), (d)), torques ((b), (e)), and forces ((c),(f)) of both hip joints during single and quadruple *pirouetté en dehors* of a representative dancer. Forces were projected to the pelvis frame. Grey and black lines: single and quadruple *pirouetté en dehors,* respectively.

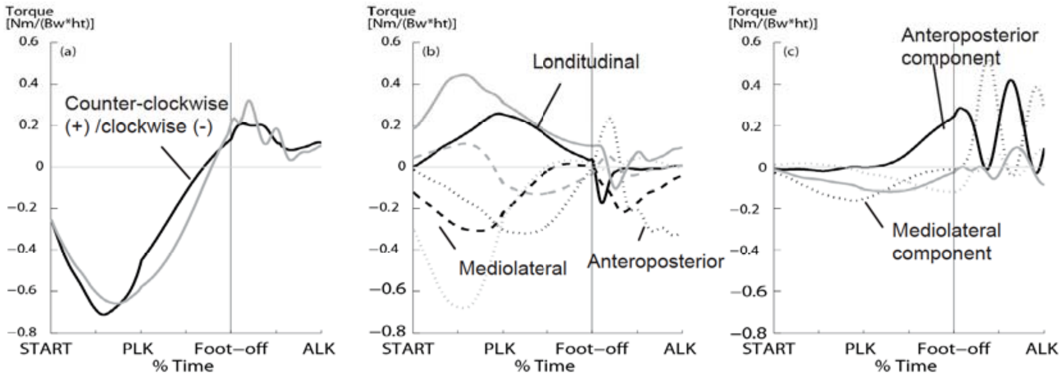

Figure 4 (a)The rate of change of the angular momentum of the upper body (black line) and the sum of the vertical components of the torques and moments of the reaction forces of both hip joints around the CoM of the upper body (grey line). (b) The vertical components of the anatomical hip joint torques around an axis through the CoM of the upper body. (c) The vertical components of the moments of the reaction forces of the hip joints around an axis through the CoM of the upper body. Grey and black lines: posterior and anterior legs, respectively. Data from quadruple *pirouetté en dehors* of a representative dancer.

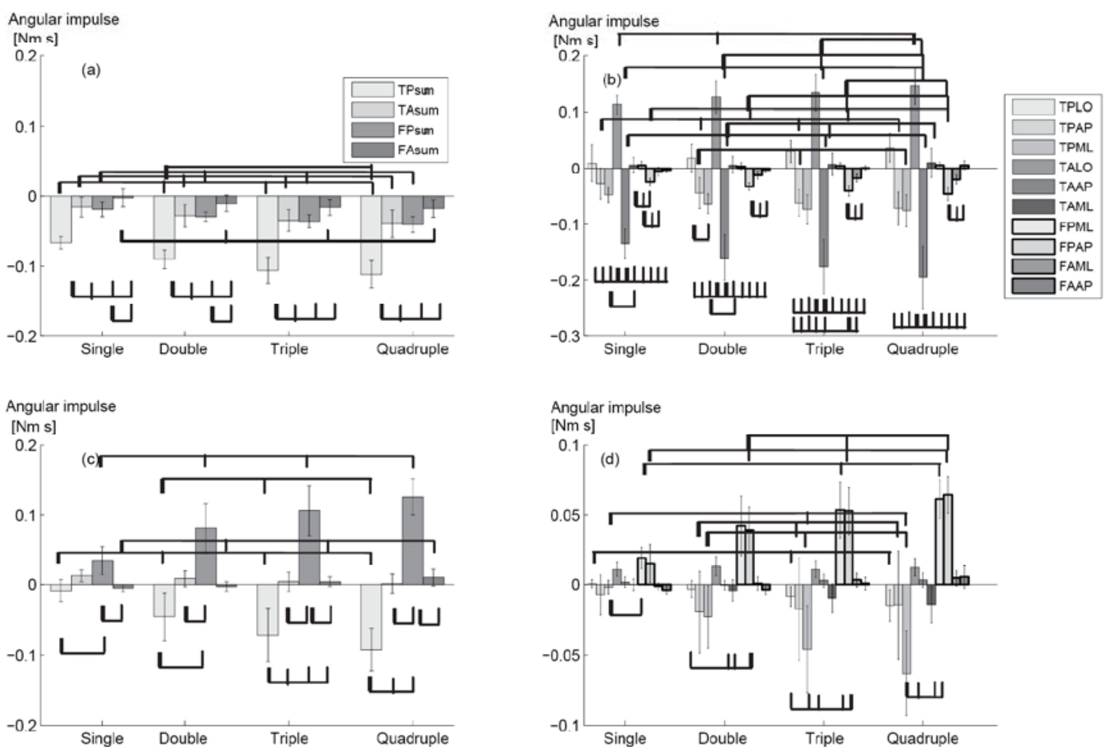

Figure 5 Angular impulses around a vertical axis through the hip joint centre (for the torques) or centre of mass of the upper body (for the moment of joint reaction forces) during the phase 1 ((a), (b)) and 2 ((c), (d)) (n=8). (a), (c): Sum of the angular impulses of the torques and moments of reaction forces of both hip joints. (b), (d): Angular impulses of the anatomical torque components and moments of reaction forces of both hip joints. **TPsum** and **TAsum**: sums of the torque components around the longitudinal axis of the hip joint of the posterior and anterior legs, respectively. **FPsum** and **FAsum**: sums of moments of the hip joint reaction forces around the longitudinal axis through the CoM of the upper body of the posterior and anterior legs, respectively. **TPLO, TPAP and TPML**: torque components of the longitudinal, anteroposterior, and mediolateral axes, respectively, of the thigh of the posterior leg. **TALO, TAAP, and TAML**: torque components of longitudinal, anteroposterior, and mediolateral, respectively, axes of the thigh of the anterior leg. **FPML, FPAP**: moments of reaction force components along the mediolateral and anteroposterior axes, respectively, of the thigh of the posterior leg. **FAML, FAAP**: moment of force components along the mediolateral and anteroposterior axes, respectively, of the thigh of the posterior leg. The angular impulses of thick vertical lines are significantly different from other angular impulses of thin vertical line with the p-value less than .05.

The contributions of the torques and moments of the reaction forces of both hip joints to the angular impulse around a vertical axis through the upper body CoM changed depending on the phases. In the phase 1, the contribution of the TPsum increased with the numbers of revolutions of *pirouetté en dehors* (Figure 5 (a)). Tthe TPAP, TAAP, FPAP and TPML contributed to the clockwise upper body rotation while the TPLO, TALO and TAML contributed to the counter-clockwise rotation of the body (Figure 4 (b)). The TALO and TAAP contributed the most to the counter-clockwise and clockwise rotation of the body, respectively, significantly in all the revolutions (Figure 5 (b)). In the Phase 2, the TPsum contributed in clockwise while the FPsum contributed in counter-clockwise (Figure 5 (c)). The FPAP and FPML contributed to the counter-clockwise upper body rotation in all the revolutions and the FPML increased with the number of revolutions (Figure 4(c), 5(d)).

DISCUSSION: The hypotheses were supported. The pelvis twisted more clockwise as the number of revolutions increased. The angle was larger in the Phase 2 than in the Phase 1. In the phase 1, mainly the TPsum acted to rotate the upper body clockwise: the hip abductor torque of the anterior leg and the hip adductor and flexor torques of the posterior leg contributed to the clockwise upper body rotation. The hip external and internal rotator torques of both legs would regulate the rotational speed of the upper body. In the phase 2, the FPsum acted to rotate the upper body counter-clockwise: the FPML and FPAP contributed to the counter-clockwise upper body rotation. The hip adductor and flexor torques of the posterior leg during the phase 1 might enable the leg to move towards the anterior leg during the phase 2 (Figure 1 (d)). However, this would decrease the upper body clockwise rotation through the FPML and FPAP during the phase 2. The hip extensor torque of the posterior leg was exerted then and contributed to the clockwise rotation. The numbers of revolutions significantly increased the contribution of the TAAP in every revolution in the phase 1. In the phase 2, the number of revolutions made differences in the contributions of the TPML and TPLO except between the single and double and triple and quadruple *pirouetté en dehors*. It might be difficult to change the joint kinetics in the two consecutive numbers of revolutions of *pirouetté en dehors.*

Referring to the study of Kim et al. (2014), the shoulder rotated clockwise more than the pelvis. The kinetics from the upper limbs would rotate the shoulder counter-clockwise despite the trunk rotated clockwise from the Start to the PLK (Kim et al., 2014). The pelvis rotated clockwise less than the shoulder through the clockwise torques and moments of force from the lower limbs. The twisting torque between the shoulder and pelvis might rotate the shoulder clockwise and the reaction of the torque might rotate the pelvis counter-clockwise.

Contribution of the anatomical torques and moment of the reaction forces of the hip joint to the torque component around a vertical axis was the opposite of the forehand and backhand stroke of the tennis (Iino et al., 2001; Akutagawa et al, 2005), hitting in softball (Iino et al., 2014). This would be due to the opposite direction of the upper body rotation. Thus, the rate of the angular and linear impulses and the mechanism of their generation during the Phase 1 would be different from those of the double stance phase of *piqué turn* (Zaferiou et al., 2016). Further studies are required to investigate the limb kinetics for the upper body rotation on the rotational direction. Differences in the personal physical characteristics need to be considered in further interpretation.

CONCLUSION: During the double stance phase of *pirouetté en dehors,* the hip adductor and flexor torques and moment of the hip joint reaction force of the posterior leg, and the hip abductor torque of the anterior leg were the main contributors of the clockwise upper body rotation. These magnitudes increased with the number of revolutions. During the following single stance phase, the angular momentum of the upper body decreased mainly by the moments of the medial and anterior hip joint reaction forces of the posterior leg. The hip joint kinetics would not be regulated depending on the numbers of rotations then. Performing multiple revolutions of *pirouetté en dehors* would require to regulate the main contributors during the double stance phase depending on the number of rotations.

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