DIFFERENT EFFECTS OF APPROACH LENGTH ON SAGITTAL AND FRONTAL JOINT KINETICS DURING A RUNNING SINGLE-LEG JUMP

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The approach lengths in running single-leg jumps (RSLJs) vary depending on various sports. We examined the effects of approach length on joint kinetics in RSLJ. We analysed RSLJs for height from the approaches of 1, 3, 5, and 7 steps by 10 male jumpers. The approach length did not have a main effect on hip extension torque (from 3.18±0.46 to 3.41±0.65 Nm/kg), while the hip abduction torque increased with increase in approach length (from 1.84±0.38 to 2.62±0.66 Nm/kg). The lumbosacral lateral flexors behaved similarly to the hip abductors. Results suggest that the greater frontal torques must be exerted from longer approaches whereas the greater hip extensors are important for RSLJs from shorter approaches. The findings provide the information for athletes what torque exertion ability should be trained with a priority depending on their approach lengths.

KEYWORDS: three-dimension, lateral flexors, abductors.

INTRODUCTION: A running single-leg jump (RSLJ) for height is a movement frequently performed in various sports, such as athletic jumping event and ball sports. The approach length in RSLJ vary depending on various sports such as 2–3 steps in basketball and handball and 7–15 steps in high jump. The longer approach results in shorter take-off durations. The take-off duration is one of the most substantial determinants of kinetics in jumping motions. Previous studies (Bobbert et al., 1987; Fukashiro and Komi, 1987) regarding various vertical jumps (hopping, bounce- or countermovement-type drop jump and countermovement jump) showed that jumping with shorter take-off duration (hopping and bounce-type drop jump) requires larger sagittal torques at the distal (ankle) joint rather than the proximal (hip) joint. Based on this, it can be speculated that the RSLJ from longer approaches might require the large ankle plantar-flexion torque rather than the hip extension torque.
In addition to lower-limb extensors, the importance of torque exertions in frontal plane have been suggested. The hip abductors and lumbosacral lateral flexors act as energy generators via elevating the pelvic free-leg side (Sado et al., 2018a). The pelvic elevation generates approximately 10% of total generated effective energy for height during the take-off of a long-jump (Sado et al., 2018b). These frontal torques are at the proximal (hip and lumbosacral) joints. If the observations on lower-limb sagittal kinetics in previous studies (Bobbert et al., 1987; Fukashiro and Komi, 1987), that jumping with shorter duration does not require larger torque at the proximal joint, can be applied to the frontal plane, these frontal torques also might not be required to increase with longer approaches. However, sagittal and frontal torques induce different segment rotations during a RSLJ take-off: the hip abductors rotate the pelvis in the frontal plane, whereas the hip extensors hardly rotate the pelvis in the sagittal plane (Sado et al., 2018a). We hypothesised that the effects of approach lengths on the frontal and sagittal torques differ. If our hypothesis is true, optimal training strategies might be different depending on the approach length used in each sports activity, but no study investigated the kinetics during RSLJs with various approach lengths.
The overall purpose of the present study was to expand the understanding of the kinetic demand in RSLJs for height with maximal efforts. For that purpose, we examined the effects of approach lengths on 3D kinetics during take-offs in RSLJs, with *a priori* hypothesis that the approach lengths have different effects on sagittal and frontal torque exertions.

METHODS: Ten male jumpers [22.0±4.6 yrs, 1.80±0.04 m, 68.8±3.4 kg, specifically (personal best) three long jumpers (6.63–7.26 m), two high jumpers (1.80–1.81 m), four triple jumpers (13.49–15.40 m), and a pole vaulter (5.15 m)] performed RSLJs as high as possible from the straight approach running of 1, 3, 5, and 7 steps, until 3 successful trials in each condition were

captured. All participants wore their own athletic shoes without spikes. A successful trial was defined as the take-off performed on a force platform. An 8-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA) and two force platforms without any changes in surfaces (Force Plate 9281E, Kistler, Winterthur, Switzerland) were used to record kinematic (sampling rate: 200 Hz) and ground reaction force (GRF) data (sampling rate: 2000 Hz). We used the whole-body marker set with 42 markers (Sado et al., 2018a).
The data were analysed using MATLAB software version 2014a (MathWorks Inc., Natick, MA, USA). The position coordinates of the markers were smoothed using a Butterworth, low-pass, digital filter with a cut-off frequency of 12 Hz which was determined by residual analysis (Winter, 2009). The GRF data were also smoothed with a cut-off frequency of 12 Hz, which was identical to that used to filter the marker position data, to prevent the artefacts soon after contact (Bisseling and Hof, 2006).
We analysed the take-off phase from the instant of touchdown to the instant of toe-off. These instants were determined by using the vertical GRF data with the threshold of 10 N. We reported the take-off duration. The centre of mass (CoM) position and the segment inertial parameters were calculated using human anthropometric data and scaling equations (Dumas et al., 2015, 2007). Newton-Euler equations were used to calculate the 3D joint torques. The joint torque was transformed into the joint coordinate system.
The peak torques during take-off phase were statistically analysed. The mean of the three trials data was used as the representative value of each condition for each participant. The normalities of all data were confirmed by the Shapiro-Wilk test. Each variable was compared by a one-way analysis of variance (ANOVA) with repeated measures. Partial eta^2 (η^2) was used to measure the effect size. Values of <0.04, 0.04–0.25, and >0.64 were indicated of small, medium, and large effect sizes, respectively. If the main effect of ANOVA was significant, pairwise comparisons were made for all pairs in the four conditions using a paired *t*-test with the Holm's adjustments. Overall statistical significance was *a priori* set at $\alpha < 0.05$.

RESULTS: The take-off duration decreased with increase in approach length (0.266±0.039 s (1 step), 0.203±0.022 s, (3 step), 0.187±0.017 s (5step) and 0.178±0.017 s (7steps)). The RoM of hip abduction-adduction (Fig. 1c) was invariant to the approach length (29.8±6.4° (1 step), 30.5±6.3° (3 steps), 30.3±4.2° (5 steps) and 30.0±5.7° (7 steps)), whereas the RoM of hip extension-flexion (Fig. 1b) decreased with the increase in approach length (57.3±9.7° (1 step), 53.1±8.3° (3 steps), 51.9±7.4° (5 steps) and 50.1±6.5° (7 steps)).
In all conditions, the lumbosacral lateral-flexion toward free-leg side (Fig. 1f), hip extension (Fig. 1g), abduction (Fig. 1h), knee extension (Fig. 1i), and ankle plantar-flexion (Fig. 1j) torques were exerted during almost the entire take-off phase. Table 1 shows the peak torques during the take-off phase. The increase in the approach length did not have main effect on the hip extension torque ($F(3,27) = 1.366$, $p = 0.280$). Conversely, the increase in approach length increased the lumbosacral lateral-flexion ($F(3,27) = 24.569$, $p < 0.001$), hip abduction ($F(3,27) = 29.031$, $p < 0.001$), knee extension ($F(3,27) = 24.994$, $p < 0.001$) and ankle plantar-flexion torques ($F(3,27) = 34.644$, $p < 0.001$).

DISCUSSION: To the best of our knowledge, this is the first study examining the effects of the number of approach steps on the 3D kinetics during take-offs in RSLJs. The findings regarding the inter-axial differences of the kinetics are novel in the present study.
Longer approaches induced shorter take-off durations. We found the increase in knee and ankle sagittal torques in longer approaches. Conversely, the approach length did not have main effect on the hip extension torque. Regarding a take-off duration in various vertical jumps, Bobbert et al. (1987) and Fukashiro and Komi (1987) observed that a shorter duration requires an increased torque at the distal (ankle) joint rather than that at the proximal (hip) joint. Thus, it can be concluded that the observations on vertical jumps can be applied to RSLJ as well.
In addition to the extensors, the torque exertions of the hip abductors (Funken et al., 2019; Sado et al., 2018a) and lumbar lateral flexors towards the free-leg side (Sado et al., 2018a) were required for RSLJ. We found that hip abduction and lumbosacral lateral flexion torques

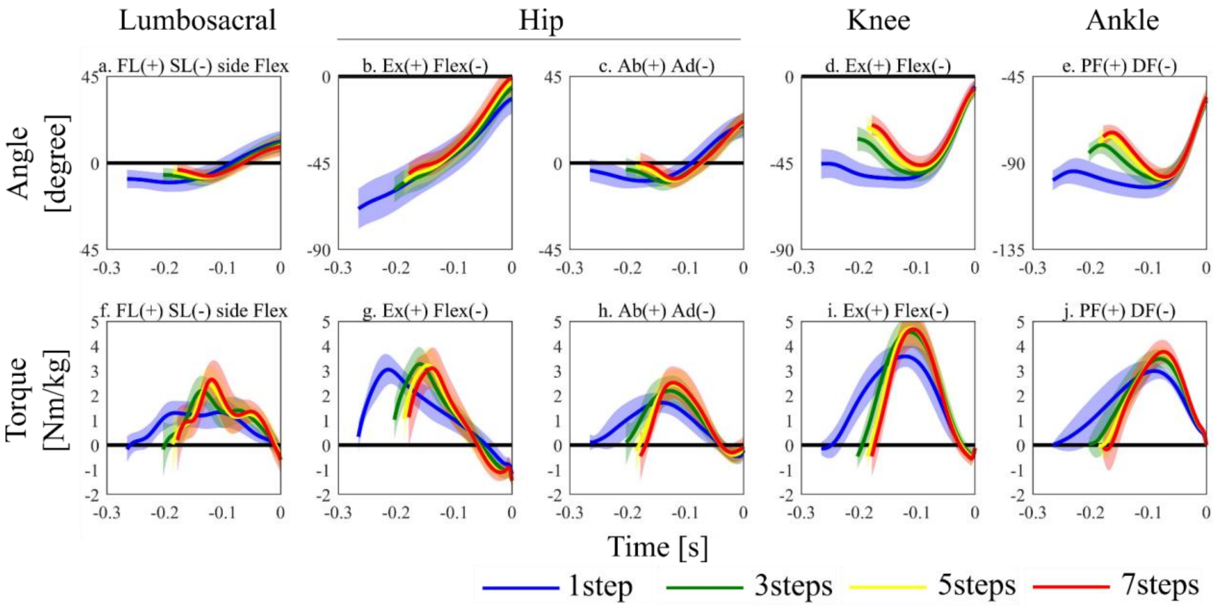

Figure 1 Ensemble averages of the joint angles, angular velocities, torques, and powers during the take-off phase in running single-leg jump. FL, free-leg; SL, stance-leg; Flex, flexion; Ex, extension; Ab, abduction; Ad, adduction; PF, plantar flexion; DF, dorsal flexion.

Table 1 Means ± standard deviations of the peak torques during the take-off phase in running single-leg jump.

Variable	Condition 1 (1 step) Mean ± SD		Condition 2 (3 steps) Mean ± SD		Condition 3 (5 steps) Mean ± SD		Condition 4 (7 steps) Mean ± SD			$\eta_{partial}^2$
LSJ_LF [Nm/kg]	1.65 ± 0.38	1,2,3	2.33 ± 0.60	1,3,4	2.65 ± 0.67	1,2	2.84 ± 0.73	1,2	*	0.73
Hip_Ex [Nm/kg]	3.18 ± 0.46		3.39 ± 0.59		3.41 ± 0.50		3.41 ± 0.65			0.13
Hip_Ab [Nm/kg]	1.84 ± 0.38	1,2,3	2.36 ± 0.62	1	2.56 ± 0.65	1	2.62 ± 0.66	1	*	0.76
Knee_Ex [Nm/kg]	3.76 ± 0.47	1,2,3	4.64 ± 0.64	1	4.77 ± 0.57	1	4.74 ± 0.70	1	*	0.74
Ankle_PF [Nm/kg]	3.08 ± 0.24	1,2,3	3.55 ± 0.47	1	3.75 ± 0.24	1	3.80 ± 0.47	1	*	0.79

Note:
LSJ: Lumbosacral joint, LF: Lateral flexion, Ex: Extension, Ab: Abduction; PF: Plantar flexion, * : Significant main effect; 1,2,3,4 : Significant difference with conditions 1, 2, 3 or 4

increased with increase in approach length, which was different from the hip extensors. This was not consistent with the observations on lower-limb sagittal kinetics that jumping with shorter duration did not require larger torque at the proximal joint in previous studies (Bobbert et al., 1987; Fukashiro and Komi, 1987); thus, the kinetic behaviours in lower-limb extensors (Bobbert et al., 1987; Fukashiro and Komi, 1987) cannot be applied on the frontal plane kinetics during RSLJ, supporting our hypothesis.

The hip abduction-adduction RoM was invariant to the approach length, whereas the hip extension-flexion RoM decreased with longer approach. The invariance of RoM in the frontal plane occurs because excessive hip abduction induces the lateral lean of overall trunk, leading to the lateral movement of the centre of mass. Thus, the invariant hip abduction-adduction RoM suggests that frontal torques in shorter approach conditions might be controlled to be sub-maximally to abduct the hip within a range that trunk does not excessively laterally lean even in longer take-off durations. This is a possible explanation for the increase in frontal torque with increase in approach length.

Our findings have practical implications for training strategies. Jumpers performing RSLJs with longer approaches, such as high jumpers, would be recommended to strengthen their hip abductors and lumbar lateral flexors as well as the lower-limb extensors. On the other hands, our results suggested that torque exertions except for hip extensors during RSLJs in shorter approaches would be controlled to be submaximal; thus, jumpers performing RSLJs with shorter approaches, such as basketball and handball players, should give greater priority for strengthening the hip extensors. Our findings would enhance the current training strategies for the jumping performances in various athletes.

Single-leg exercises, such as single-leg squat and rebound jump, are used to strengthen the ability of frontal torque exertions (Kariyama et al., 2017). Based on our findings, the single-leg exercises with smaller lower-limb extension displacements performed in shorter durations might induce a larger load to strengthen the frontal torque exertion abilities. Clarification of the effects of the duration in various exercises on the training effect of frontal torque exertion abilities is an important future theme to expand the understanding of single-leg exercises.

The present study had some limitations. First, we collected the data only from athletic jumpers. Our findings might not necessarily be true for all team sport players. However, the results suggest that the increase in frontal torque with longer approaches relate to the RoM in the frontal plane. Therefore, we speculated that the effects of approach lengths on frontal kinetics would not critically change in players of other team sports. Second, although this is the study focusing on the kinetic demand to simply jump as high as possible, team sports players attempt to do something in addition to simply jumping; thus, the findings in this study might not applied on RSLJ execution during games. Third, we could not collect the data for the RSLJs with an approach length greater than 7 steps due to the limited space in the laboratory. Future studies to examine the RSLJs with longer approach lengths are necessary. Forth, the sample size (10 participants) in this study might be small to detect significant differences in the *post hoc* test. Future studies using a larger sample size might be needed to confirm the differences between the approach length conditions; however, this limitation would not change our finding of the inter-axial differences in the effects of the approach length in RSLJs on joint kinetics in ANOVA.

CONCLUSION: We found that the shorter take-off duration due to longer approaches requires larger torque exertion more in the distal joint than in the proximal joint in the sagittal plane, and that the lumbosacral and hip frontal torques are required to increase with increase in approach lengths, although they are exerted at the proximal joints. The findings regarding inter-axial differences expand the understanding of the musculoskeletal demand in RSLJ, which has useful implications in the design of optimal training programs to improve jumping performance.

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