LEG AND VERTICAL STIFFNESS OF TRANSFEMORAL AMPUTEES USING RUNNING-SPECIFIC PROSTHESES

Yoko Sano[1,2] , Hiroaki Hobara[1], Yoshiyuki kobayashi[1], Satoru Hashizume[1], Akihiko Murai[1], Atsushi Makimoto[1,2], Hiroshi Takemura[2]

National Institute of AIST, Tokyo, Japan[1]
Tokyo University of Science, Chiba, Japan[2]

Since running-specific prostheses (RSPs) emulate spring-like leg functions, human musculoskeletal system is often modelled as a spring-mass model. In the model, the leg (K_{leg}) and vertical stiffness (K_{vert}) is known to strongly influence running performance. The purpose of this study was to quantify the asymmetry in stiffness between the intact limbs and prosthetic limbs during sprinting. Eight sprinters with unilateral transfemoral amputation performed overground sprinting at maximum speed. K_{leg} and K_{vert} were calculated from vertical ground reaction force data in both the intact and prosthetic limbs. K_{leg} was significantly greater in intact limbs than prosthetic limbs. Although there was no significant difference on K_{vert}, cohen's d of K_{vert} between legs was 1.28. Therefore K_{vert} might have potential significant difference.

KEY WORDS: prosthetic sprinting, leg spring, spring mass model.

INTRODUCTION: During running, the musculoskeletal structures of the legs alternately store and return elastic energy. This is because the nervous system coordinates the actions of the many muscle in the stance limb with the actions of the many muscles, tendons and ligaments so that the overall system behaves similarly to a single spring during running (He, Kram & McMahon, 1991; Farley, Glasheen & McMahon, 1993). Therefore, the body is modelled as a “spring-mass model”, which has been widely used to describe the mechanics of running (Blickhan, 1989; McMahon & Cheng, 1990). This model consists of a massless linear leg spring and a particle representing the center of mass (COM) of the entire body. Using the model, it is possible to define and measure the leg (K_{leg}) and vertical stiffness (K_{vert}). K_{leg} and K_{vert} are well related to running performance (He, Kram & McMahon, 1991; McGowan et al., 2012; Cavagna, Heglund & Willems, 2005). Several studies investigated the K_{leg} and K_{vert} in transtibial amputees, and found that K_{leg} in prosthetic (PST) side was on average 27%-35% lower than intact (INT) side in this populations (McGowan et al., 2012; Hobara et al., 2013). Stiffness inbalances between limbs could be detrimental to performance or could increase soft tissue injury risk (Eamonn & Andrew, 2007). And understanding the asymmetry of stiffness in running lead to identifying injury risk factors (Hobara et al., 2013). However little is known about stiffness regulations during running in transfemoral amputees. The aim of this study was to quantify the asymmetry in K_{leg} and K_{vert} between the INT and PST.

METHODS: Eight sprinters with unilateral transfemoral amputation participated in this study (5 males and 3 females, height:1.61 ± 0.09 m, mass:55.5 ± 9.75 kg, 100-m personal records:17.2 ± 2.47 s). All participants used the same type of prosthetic knee joints (3S80, Ottobock) and RSPs (1E90 Sprinter, Ottobock). They performed maximum sprinting on over 40 m runway and we analysed vertical ground reaction force (vGRF) data of the accelerated phase for successful 4 trials. vGRF was collected using seven force plates in the middle of 40m runway sampled at 2000 Hz. The vGRF data was filtered using a zero-lag fourth order low pass Butterworth filter with cut-off frequency of 75 Hz. K_{leg} was calculated as the ratio of peak vertical force ($\mathrm{vGRF}_{\mathrm{peak}}$) and maximum change in length of the virtual leg spring (ΔL):

$$K_{leg} = \mathrm{vGRF}_{\mathrm{peak}} / \Delta L. \quad (1)$$

ΔL was calculated from the maximum vertical displacement of COM (Δy), the standing leg length (L_0), and half of the angle swept by the leg spring while it was in contact with the ground (θ). Vertical displacement of COM was calculated from double integration of the COM acceleration (y_a) with respect to time. y_a was calculated from vGRF that was measured by the force plates and body mass (m):

$$\Delta L = \Delta y + L_0(1\text{-}\cos\theta). \quad (2)$$

$$y_a(t) = \{ \text{vGRF}(t)\text{-mg} \} / \text{m}. \quad (3)$$

K_{vert} was determined from the regression slope of the profile where the vGRF was plotted against the COM displacement up to maximum vGRF. K_{leg} and K_{vert} were normalized by the subjects' body weights. Assuming that the lower extremities behave according to a simple spring-mass model, the correlation between vGRF and COM displacement during the ground contact phase should be greater than r = 0.80 (Granata, Padua & Wilson, 2002). Thus, we confirmed whether the correlation coefficient between the latter two variables was >0.80 for the subject. Dependent t-tests ($p < 0.05$) were performed to compare the stiffness of INT and PST at sprinting by using SPSS and effect sizes (Cohen's d) was also performed.

RESULTS: The average velocity of all subjects was 5.55±0.80 m/s. Figure 1 shows a typical example of the relationship between vGRF and vertical COM displacement during the stance phase. The correlations between the vGRF and COM displacement up to maximum vGRF w were 0.96 and 0.98 in INT and PST, respectively.

Figure 2 shows comparisons of K_{leg} and K_{vert} between INT and PST. K_{leg} in PST was 39.3% lower than that of INT (d = 1.80). However there was no statistical significant difference on K_{vert} (d = 1.28).

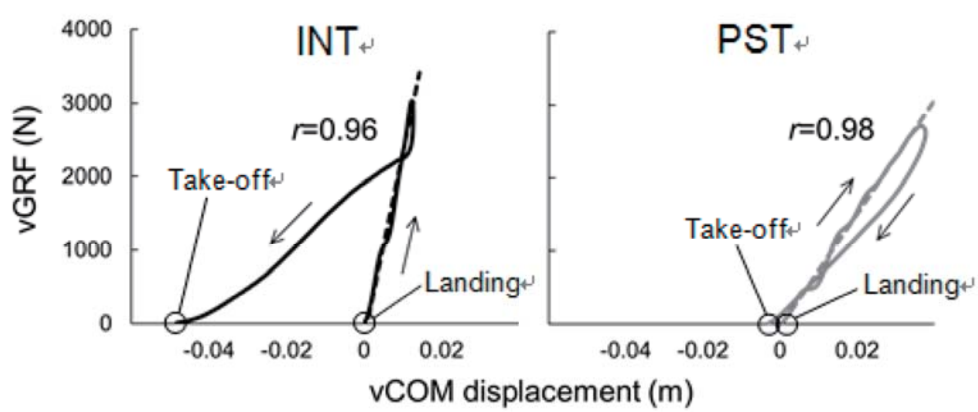

Figure 1: vGRF-COM displacement curves during ground contact for the INT and PST, respectively. The slopes (dotted lines) of these curve represent K_{vert}.

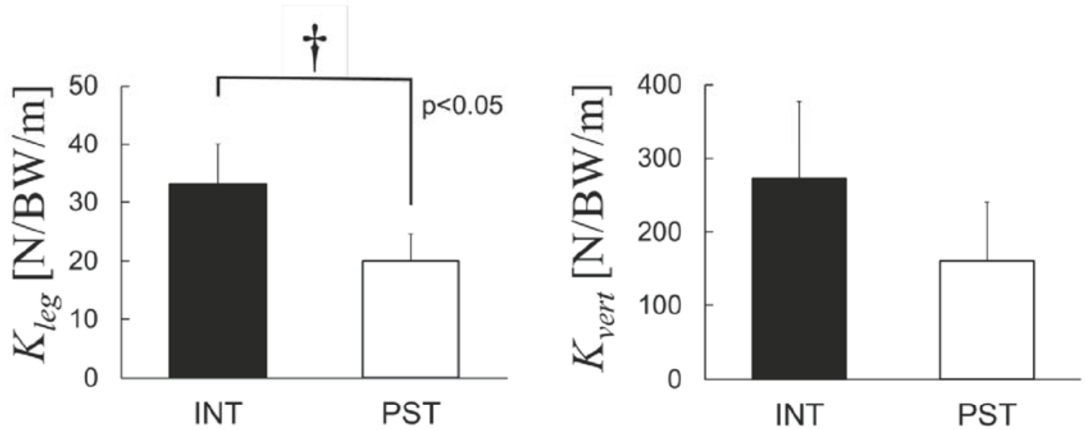

Figure 2: Comparisons of K_{vert} and K_{leg} between INT and PST.

DISCUSSION: As shown in Figure 1, the curve in INT depicts different behaviours in the first and second half of the stance phase. On the other hand, the curve drawn by PST in the first and second half were similar. These results may represent that PST can only release potential energy stored while INT release potential energy more than stored. This suggests that other energy has been changed to potential energy in INT. As shown in figure 2, we also found that K_{leg} in PST were significantly lower than INT (p = 0.004). Although there was no significant difference on K_{vert} (p = 0.094), cohen's d of K_{vert} between legs was 1.28. Therefore K_{vert} might have potential significant difference. These results agreed with previous studies which demonstrated that INT have a greater K_{leg} and K_{vert} than PST during overground running in transtibial amputees (McGowan et al. 2012; Hobara et al. 2013). However, the difference of these variables between both legs in transfemoral amputees is greater than in transtibial amputees (27-35%) reported in previous studies (McGowan et al., 2012; Hobara et al., 2013). Our data also showed that peak vGRF was significantly greater in INT than PST, while there was no significant differences in ΔL and maximum vertical COM displacement. Therefore, K_{leg} during running in transfemoral amputees would be greatly affected by peak vGRF rather than by ΔL and maximum vertical COM displacement. Since the different stiffness affects loading rate to lower extremities (Hobara et al.,2013), it may be exposed greater risk of secondary cumulative injuries.

CONCLUSION: The results of the present study showed that K_{leg} in PST were about 40% lower than those of INT and there was no significant difference on K_{vert} during maximum sprinting in unilateral transfemoral amputees. Since stiffness inbalances between limbs could increase soft tissue injury risk, INT in transfemoral amputees might be exposed to higher injury risk.

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Acknowledgement