# A BIOMECHANICAL ANALYSIS OF THE SUPPORT MECHANISM OF THE TAKEOFF LEG IN THE LONG JUMP

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The purpose of this study was to investigate the function of the takeoff leg as a support mechanism in the long jump with the mechanical model (Shibukawa et al., 1966). The mechanical model assumed that the force exerted by the takeoff leg was equivalent to the sum of the spring, damper and jack forces. Eleven male long jumpers participated in this study. Large spring and damper forces were exerted and absorbed the impact force immediately after the touchdown, and the spring force was also exerted around 25 to 80% of the takeoff phase. The jack force was dominant in two thirds of the takeoff phase. The comparison between the elite jumpers and the ordinary college level jumpers indicated that larger spring force around 25 to 50% of the takeoff phase of the ordinary college level jumpers would result from larger knee flexion.

**KEY WORDS:** long jump, takeoff, mechanical model, spring, damper, jack.

**INTRODUCTION:** In the takeoff of the long jump a jumper should obtain vertical velocity of the center of gravity (CG) while retaining as much horizontal velocity of the CG as possible. Since the takeoff leg of the long jumper plays a very important role to convert the horizontal velocity to the vertical one by generating large force to the ground, the support mechanism of the takeoff leg should be investigated to understand takeoff mechanics and improve the performance of the long jump. Although several types of mechanical models (Alexander, 1990; Blickhan, 1989; Seyfarth, 1999) have been available, most of them are a simple spring-mass model in which the spring constants (stiffness) are assumed to unchange during the takeoff. However, it would be natural that the stiffness of the takeoff leg varies with the change in position of the joint and the muscle activity during the takeoff. Shibukawa et al. (1966) proposed a mechanical model of the takeoff leg that consisted of three mechanical elements: spring, damper, jack which were assumed to change with the changes in the displacement and velocity of the CG during the takeoff. The purpose of this study was to investigate the function of the takeoff leg as a support mechanism in the long jump with the mechanical model proposed by Shibukawa et al. (1966).

**METHODS:** The subjects were eleven male long jumpers: four elite jumpers with the best performance of 7.83 to 8.15 m and seven ordinary college level jumpers of 6.45 to 7.41 m. The takeoff motion of the subjects with full run-up was videotaped with a high speed video camera (200-250 fps). Ground reaction forces (GRF) during the takeoff were collected with a force platform (1kHz). Two dimensional coordinates of the body landmarks were obtained by digitizing VTR images. LED signal was used to synchronize the GRF data with the VTR data. Figure 1 shows the mechanical model and the elements (Shibukawa et al., 1966) used in this study. In the model the takeoff leg is assumed to have two functions: passively supporting the body mass represented by a spring and damper and actively supporting and moving the body mass represented by a jack. Therefore, the GRF exerted by the takeoff leg was considered to be equivalent to the sum of the spring, damper and jack forces. Figure 2 shows the definition of the radial direction of the CG movement. In this study the radial direction was defined as the direction from the center of rotation (C), the mid point between the big toe and heel at the maximum knee flexion, to the CG. The distance between the C and the CG (the CG length) was referred to as $\mathbf{r}$ and the rate of the CG length change was as $\dot{\mathbf{r}}$. The spring force is proportional to $\mathbf{r}$ and the damper force is proportional to $\dot{\mathbf{r}}$, and the direction of the force is opposite to $\mathbf{r}$ and $\dot{\mathbf{r}}$, respectively. Since the proportional coefficients for the spring and damper are represented by k and c, the spring force and the damper force are represented by $-k^*\mathbf{r}$ and $-c^*\dot{\mathbf{r}}$, respectively. Consequently, the force exerted by the takeoff leg ($F_r$) is the sum of the three force elements, as represented by the following equation:

$$\mathbf{F}_r = (-\mathbf{k} * \mathbf{r}) + (-\mathbf{c} * \dot{\mathbf{r}}) + \mathbf{f} \quad (1)$$

where f is the jack force and $F_r$ represents the radial component of the GRF. The coefficients k and c are changeable with the change in position of the joint and the muscle activity during the takeoff phase. However, if we assume that the coefficients k and c unchange in a very short interval of time (0.004-0005 s), we can estimate k, c and f as a solution of 3 by 3 determinant with $F_r$, $\mathbf{r}$ and $\dot{\mathbf{r}}$ as follows:

$$\begin{aligned} \mathbf{F}_{ri-1} &= (-\mathbf{k}_i * \mathbf{r}_{i-1}) + (-\mathbf{c}_i * \dot{\mathbf{r}}_{i-1}) + \mathbf{f}_i \\ \mathbf{F}_{ri} &= (-\mathbf{k}_i * \mathbf{r}_i) + (-\mathbf{c}_i * \dot{\mathbf{r}}_i) + \mathbf{f}_i \quad (2) \\ \mathbf{F}_{ri+1} &= (-\mathbf{k}_i * \mathbf{r}_{i+1}) + (-\mathbf{c}_i * \dot{\mathbf{r}}_{i+1}) + \mathbf{f}_i \end{aligned}$$

where suffix $i$ represents $i$ th time from the takeoff foot touchdown. Since the coefficients k and c are more than zero and all of three mechanical elements of the model are positive, the spring force and the damper force appear when $\mathbf{r}$ and $\dot{\mathbf{r}}$ are negative. These forces are calculated by the programs written in MATLAB (MathWorks Corp.). The data of all subjects were normalized by the time of the takeoff phase and averaged.

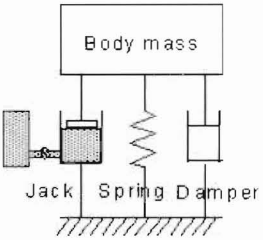

Figure 1 Illustration of the mechanical model (Shibukawa et al., 1966).

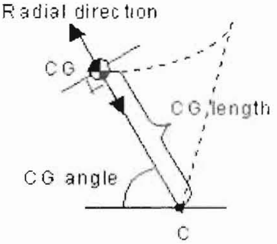

Figure 2 Definition of the radial direction. CG, the center of gravity; C, the center of the rotation (mid point between the big toe and heel at maximum knee flexion).

**RESULTS AND DISCUSSION:** During the takeoff phase, the average horizontal velocity of the CG was 8.29±0.51 m/s (the elite jumpers 8.81±0.28 m/s, ordinary college level jumpers 7.99±0.33 m/s). The average of the contact time during the takeoff phase was 0.118±0.012 s (the elite jumpers 0.108±0.012 s, ordinary college level jumpers 0.123±0.009 s). Figure 3 shows changes in the displacement, velocity and component of the GRF in the radial direction during the takeoff phase for both subject groups. The radial CG displacement decreased after the touchdown to a minimum about 40% of the takeoff phase and increased until the toeoff. The change in the knee joint would have large effect on the change of the CG length. The radial CG velocity increased through the takeoff phase, changing from the negative value to the positive about 40%. The radial component of GRF rapidly increased immediately after touchdown and reached to the peak about 10% and the second peak about 40% of the takeoff phase. Based on the change in the GRF, the impact phase was defined from the touchdown to 20% of the takeoff phase. Figure 4 shows changes in the spring, damper and jack forces during the takeoff phase for both subject groups. Large spring and damper forces were exerted sequentially to absorb the impact force immediately after the touchdown, and then the spring force was exerted again around 25 to 80% of the takeoff phase. The jack force was dominant in two thirds of the takeoff phase. The damper force did not appear after the impact phase. In the impact phase, the radial component of the GRF of the elite jumpers was larger than that of the ordinary college jumpers immediately after the touchdown. This resulted from the quicker and larger exertion of the spring and damper forces of the elite jumpers than the ordinary college level jumpers. This indicates that the elite jumpers can exert large spring and damper force at the instant of the touchdown to resist large impact force and to support the body mass. Since the reduction of the CG length of the ordinary college level jumpers was larger than that of the elite jumpers, the ordinary college level jumpers exerted larger spring force around 25 to 50% of the takeoff phase.

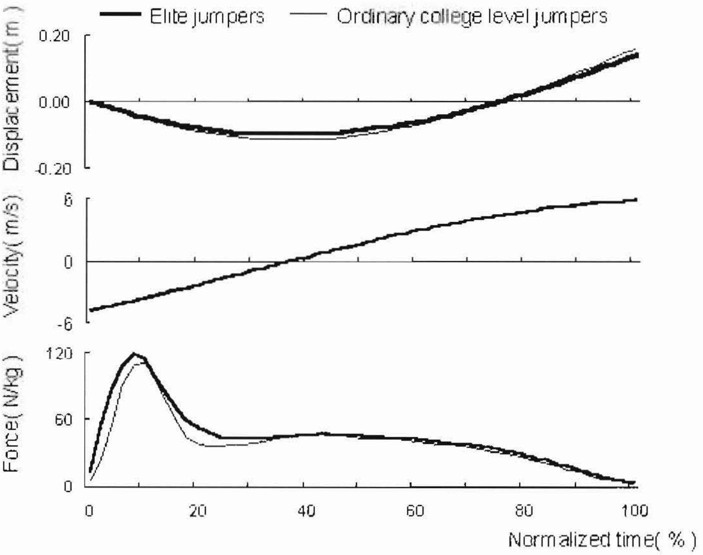

**Figure 3.** The average radial CG displacement and its velocity and the radial component of the GRF patterns during the takeoff phase (elite jumper and ordinary college level jumper group).

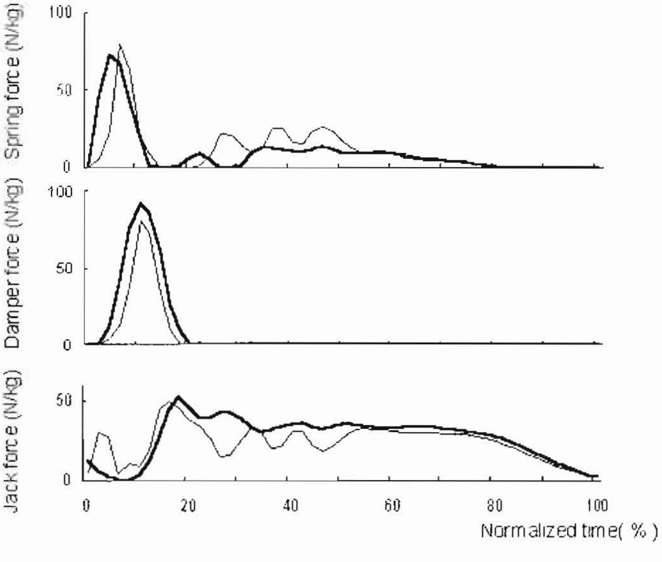

**Figure 4.** The average spring, damper and jack force patterns during the takeoff phase (elite jumper and ordinary college level jumper group).

However, the knee joint of the takeoff leg for the ordinary college level jumpers would flex largely during the takeoff phase, and the ordinary college level jumpers should not be able to extend it rapidly.

**CONCLUSION:** The spring force resisted the impact force immediately after the touchdown. The damper force was exerted to absorb the impact force and to support the jumper's body. The jack force was dominant in the most part of the takeoff. The comparisons between the elite jumpers and the ordinary college level jumpers indicated that larger spring force around 25 to 50% of the takeoff phase of the ordinary college level jumpers would result from larger knee flexion. Therefore, it was suggested that jumpers should place the takeoff foot with the extended knee joint to avoid too much knee flexion after the touchdown.

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