LEG- AND JOINT STIFFNESS IN MALE ELITE HIGH JUMP: THE INFLUENCE OF STIFFNESS ON SPORTS PERFORMANCE

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The purpose of this study was to analyse stiffness in the mechanical system of the world's elite high jumpers. Seven male elite high jump athletes (personal best 2.24 m ± 0.06 m) were filmed with 19 Infrared-High-Speed-Cameras during jumping. Kinetics were captured with a force plate. It was found that a different leg and joint stiffness during take-off enables nearly the same jumping height. For example, a typical power jumper with a leg stiffness of 543.6 N m^{-1} kg^{-1} reached 2.13 m, while a typical speed jumper with a leg stiffness of 1133.5 N m^{-1} kg^{-1} reached a comparable height of 2.12 m. Therefore, it seems that sports performance in single leg jumping is not limited by athlete's leg and joint stiffness in a small group of male elite high jumpers.

KEY WORDS: single leg jumping, take-off.

INTRODUCTION: The mechanical aim of a high jump is the optimized superposition of vertical and horizontal velocity to displace the body's centre of mass (COM) to maximum height. Therefore, the athlete generates upward velocity out of the horizontal acceleration by using the energy output at the joints of the lower extremities. In this kind of energy transformation our legs exhibit characteristics similar to those of a spring, which is compressed during the first half of the stance phase and rebounds during the second half (Farley & Ferris, 1998). The high jumpers use this effect to increase their height: they generate upward speed out of the opposite directional impulse of the ground, which is only possible with certain mechanical stiffness in legs and joints (Farley et al., 1991; Arampatzis et al., 2001). The relationship between mechanical stiffness and sports performance is of great interest to sport and research communities. Unfortunately, these relationships are relatively unexplored by researchers, especially for single leg jumping. Several studies have examined the relationship between stiffness and performance during two-legged hopping (e.g. Farley et al., 1991; Granata et al., 2001) and running (e.g. Arampatzis et al., 1999; Kuitunen et al., 2002). Only two studies examined the effects of stiffness on single leg jumping performance (Seyfarth et al., 2000; Laffaye et al., 2005). Both studies did not determine stiffness in a sport specific situation. However, regarding the results of the different studies, lower extremity stiffness increases with the demands of the activity (e.g. speed or frequency), whereas during single leg jumping it seems that leg stiffness does not need to be increased in order to enhance performance. Yet, it is unclear whether mechanical stiffness of the lower extremity is influenced in human all-out situations (e.g. elite high jump). Hence, the study aims to analyse stiffness in the mechanical system of the world's elite high jumpers.

METHODS: Motions of seven male athletes (personal best 224 cm ± 6 cm) during jumping were filmed with 19 Infrared-Highspeed-Cameras (300 Hz, Vicon, Oxford, UK) and ground reaction forces were captured with a force plate (1200 Hz, Kistler, Winterthur, Switzerland). Kinematics of the full body were determined using 69 retro-reflective, spherical markers. To analyse the different stiffness parameters in the lower limbs, the knee and ankle joint, a spring-mass and torsional spring model were used (Farley & Morgenroth, 1999). The leg stiffness was calculated by dividing the peak of the resultant ground reaction force by the peak of leg compression, which is equal to the distance between the trochanter major and the malleolus lateralis during touch-down and maximum compression. Whereas the joint stiffness was calculated as the ratio of peak joint moment to peak joint angular displacement. All values were divided by the athlete's body masses (Farley & Morgenroth, 1999). A Wilcoxon signed-rank test was used to identify significant differences in the joint stiffness properties. The level of significance was defined as $\alpha = 0.05$.

RESULTS: Five of seven athletes crossed the bar at 2.10 m, one at 2.05 m and one at 2.00 m. The highest COM position was captured at 2.19 m. Horizontal run-up velocities ranged between 5.92 ms^{-1} and 7.25 ms^{-1}. Maximum resultant ground reaction forces attained 64 N kg^{-1} to 84 N kg^{-1}. Joint stiffness of the seven high jumpers during take-off differed between 6.5 Nm rad^{-1} kg^{-1} and 11.7 Nm rad^{-1} kg^{-1}, whereas leg stiffness differed between 543.6 N m^{-1} kg^{-1} and 1133.5 N m^{-1} kg^{-1} (Table 1).

Table 1
Athletes' performance and stiffness specifications

athlete	A01	A02	A03	A04	A05	A06	A07	MD	SD
COM [m]	2.18	2.13	2.12	2.03	2.16	2.11	2.14	2.13	0.05
v_{run-up} [m/s]	6.76	5.92	7.25	6.56	7.02	6.82	7.11	6.87	0.43
BW [kg]	71	85	79	70	75	77	74	76	5
k_{leg} [N m^{-1} kg^{-1}]	578.3	543.6	1133.5	721.1	1023.7	1134.5	761.1	842.3	252.7
$k_{ankle\ joint}$ [Nm $rad^{-1}kg^{-1}$]	8.8	7.5	9.0	7.5	8.1	6.5	8.3	8.0	0.9
$k_{knee\ joint}$ [Nm $rad^{-1}kg^{-1}$]	10.2	9.3	11.0	9.3	11.7	11.7	9.8	10.4	1.0

Centre of mass (COM) above ground, run-up velocity (v_{run-up}) and the athlete's bodyweight (BW). Leg stiffness (k_{leg}), ankle ($k_{ankle\ joint}$) and knee stiffness ($k_{knee\ joint}$) of the seven athletes. A02 represents a typical power jumper; A03, A05 and A07 are typical speed jumpers. Including mean (MD) and standard deviation (SD).

DISCUSSION: Leg stiffness ranged from 543.6 N m^{-1} kg^{-1} to 1133.5 N m^{-1} kg^{-1}. Seyfarth et al. (2000) calculated in a simulation study that there was a minimal level of leg stiffness about 16.2 kN/m (202.5 N m^{-1} kg^{-1}) required for maximizing jumping distance in long jumping. Interestingly, an increase in leg stiffness did not result in longer jumps. Therefore, a task specific optimum of mechanical stiffness seems advantageous for maximum performance. The high jumpers with the highest COM positions (A01: 2.18 m and A05: 2.16 m) showed leg stiffness of 578.3 N m^{-1} kg^{-1} and 1023.7 N m^{-1} kg^{-1}. In contrast, the jumper with the lowest COM position (A04: 2.03 m) had a leg stiffness of 721.1 N m^{-1} kg^{-1}. Further, the speed jumpers (v_{run-up} > 7 ms^{-1}: A03, A05, A07) stiffened their leg during take-off from 761.1 N m^{-1} kg^{-1} to 1133.5 N m^{-1} kg^{-1}. On the other side, the jumper with the highest leg stiffness (A06) only raised his COM to the second lowest height (2.11 m) when crossing the bar. Therefore, a relation between run-up velocity and leg stiffness in elite high jump was observed, but not between leg stiffness and performance. Also Laffaye (2012) argued that, when zooming on a specific population that does not mean that the best value of stiffness will give the winner of the competition. This was also found for joint stiffness. The highest jumpers did not have the highest joint stiffness. During take-off, mean joint stiffness at the knee was 10.4 Nm rad^{-1} kg^{-1} and thus higher than at the ankle (8.0 Nm rad^{-1} kg^{-1}). Indeed, Hobora et al. (2008) also showed that the stiffness at the knee joint was little higher than at the ankle in distance runners and power trained athletes. Regarding individual data, this tendency was found for all high jumpers. During high jump, ankle joint stiffness is about 40% higher than during

sprint running (Stefanyshyn & Nigg, 1998). Comparing the stiffness of the different jumping styles, the typical power jumper (A02) had a lower leg and joint stiffness than the typical speed jumpers (A03, A05, A07) had.
During take-off, the ankle joint absorbed energy during the first half of the stance phase when the ankle was dorsiflexing and generated energy during the second half when the ankle was plantar flexing. But analysis of leg and joint stiffness and the link to muscle and tendon properties is quite complex. Nevertheless, the compliance of a tendon heavily influence the amount of energy delivered to the skeleton by a muscle. For the knee extensors, which have relatively short and stiff tendons, the total energy delivered to the skeleton was dominated by the contractile element. In contrast, for the ankle plantarflexors, which possess longer and more compliant tendons, the total energy delivered to the skeleton was dominated by the elastic tissue (Anderson & Pandy, 1993). Therefore, it seems reasonable that the ankle is less stiff during single leg jumping than the knee or the hip are.

CONCLUSION: Although a relation between run-up velocity and leg stiffness was observed, the inconsistent relation between mechanical stiffness and elite high jump performance showed that an athlete specific optimum of mechanical stiffness seems advantageous for maximum performance. It was found that a different leg and joint stiffness during take-off enables nearly the same jumping height. It seems that sports performance in single leg jumping is not limited by athlete's leg and joint stiffness in a small group of male elite high jumpers. Regardless of whether they are power jumpers or speed jumpers, the jumpers have the possibility to compete successfully at the same level with different lower extremity stiffness. Additional information about muscle and tendon properties would provide more insight into its effect on sports performance.

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