

ASSOCIATION OF MUSCLE-TENDON MECHANICAL PROPERTIES AND JUMPING PERFORMANCE – SOME BIOMECHANICAL CONSIDERATIONS

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Jumping performance in sports was structured at a first glance. Then one-legged take-offs build the focus of the impact of mechanical properties of the muscle-tendon complex and its association to jumping performance. These considerations were consequently transferred to the typical one-legged take-off in sports – the running long jump. Long jump performance is up to 90% determined by the flight distance of the athlete's centre of mass is determined by the run-up and the accelerations of the swinging leg and the swinging arms, and the net joint moments at the metatarsalphalangeal joint, the ankle, the knee and the hip joints during the ground contact of take-off. The energy storage and return concept in tendons and ligaments of foot, ankle and knee and potential of energy storage and return was critically discussed. Relevance of mechanical properties of tendons' and ligaments' has shown some evidence of higher tendon stiffness in elite athletes in jumping events. It was also speculated that a low hysteresis or energy dissipation should have an impact to jumping performance.

KEY WORDS: Take-off mechanics, long jump, mechanical properties, muscle-tendon unit

INTRODUCTION: This contribution discusses the association between muscle-tendon mechanical properties and their possible impact to jumping performance. Jumping in sports is characterized by a short ground contact time for the take-off in which significant changes in the centre of mass trajectory occur. In the same time during take-off changes of angular momentum may take place with a transfer of linear momentum to angular momentum e.g. in the high jump take-off or in the take-off for a running forward somersault in gymnastics or with a transfer of angular momentum to linear momentum e.g. in a double backward somersault take-off after a flic-flac (handspring backwards) in floor gymnastics or tumbling. A number of take-offs in sports are performed on highly deformable visco-elastic surfaces with a great potential to store and re-utilize elastic energy in the sport surface. Other take-offs occur on stiff visco-elastic surface like the take-off of the long jump or the high jump in athletics. Some take-offs are performed from one leg like the long or the high jump others are from both legs like most of the take-offs in gymnastics. Some take-offs are from a squat position without counter movement or from a standing position with a counter movement and eccentric muscle action prior the concentric muscle activity in the push-off. The majority of take-offs are related to a fast stretch-shortening cycle of the extensor muscles of the ankle, the knee and the hip joints. Many take-offs are characterized by a large amount of initial mechanical energy of the entire body through a run-up or similar motor actions prior to take-off. Those take-offs which are performed from a standing or squat position should be primarily determined by muscle force and therefore by the mechanical and neuro-muscular properties of the muscle in terms of muscle volume and muscle power. Take-offs with initial energy should strongly be related to energy storage and return or to minimization of energy loss. The mechanical properties of the muscle-tendon-units and probably the mechanical properties of ligaments may play an important role in jumping performance with high initial energy through a fast approach run like in the running long jump. Two-legged jumps and especially those from a standing position (e.g. counter movement jumps) are frequently studied and described. This contribution concentrates on one-legged jumping from a stiff abutment and with sufficient approach energy. The running long jump is chosen as the athletic representative of this form of jumping in sports.

LIMITING FACTORS OF LONG JUMP: In the long jump the athlete's objective is to obtain a maximum displacement of the centre of mass in the horizontal direction and "then, in keeping with the rules governing the event, to extract as much credit as possible for having achieved this displacement" (Hay, 1985). In the long jump the athlete endeavours to get the feet as far forward as possible without falling back on landing. The distance with which the athlete is

credited in the long jump can be considered to be the sum of three distances: (1) The take-off distance (TD), the horizontal distance between the front edge of the take-off board and the athlete's centre of mass at instant of take-off; (2) The flight distance (FD), the distance that the centre of mass travels while the athlete is in the air; (3) The landing distance (LD), the horizontal distance between the centre of mass at the instant the feet hit the sand and the marks in the sand from which the distance of the jump is ultimately measured. The contribution of each of these distances makes to the total distance jumped e.g. by athletes of the 1997 World Championships around 3% (TD), 90 % (FD), and 7% (LD). The take-off distance is a function of the accuracy with which the jumper places the foot on the take-off board, the athlete's anthropometric properties, and the body position at instant of take-off. The flight distance is governed by centre of mass take-off velocity, angle of take-off, height of centre of mass at take-off relative to landing height and the air resistance encountered in flight. The landing distance depends on the athlete's body position at touchdown in the landing pit and on the actions avoiding falling back and reducing the measured length of the jump. The principal factors influencing the body position at touchdown are the initial body position at take-off, the angular momentum during flight and the duration of the flight. The angular momentum and the body position at touchdown also influence the risk and affects the actions counteracting falling back after landing in the pit.

The take-off velocity and the take-off angle are dependent of the horizontal velocity of athlete's centre of mass at the instant of touchdown for the take-off - the run-up velocity - , the vertical centre of mass velocity at instant of touchdown, the horizontal and the vertical impulses during take-off, and the athlete's mass. The change of the trajectory of centre of mass is between 16° and 23° . In successful jumps of elite jumpers total body mechanical energy slightly increases during take-off. Less successful long jumps are characterized by a decrease of total body energy.

TAKE-OFF BIOMECHANICS: During take-off the athlete's centre of mass decreases horizontal and increases the vertical speed due to the horizontal and vertical impulses acting on the centre of mass. The impulses generated by the horizontal and vertical ground reaction forces are the result of the acceleration of the swinging arms and the swinging leg, and the net joint moments of the hip, the knee, the ankle joints, and the metatarsophalangeal joints (MPJ) of the take-off leg. All four driving joints receive eccentric muscle-tendon loading in the first part of the take-off and concentric muscle action in the second part. Hip, knee, ankle joints, and MPJ of the take-off leg absorb energy first and generate energy in the second half of take-off. While the MPJ only absorb energy during take-off and has no potential to generate mechanical energy by its driving muscles (m. flexor halucis longus, m. flexor digitorum), Stefanyshyn & Nigg (1998) reported from running long jumps, that the ankle joint absorb 133 ± 15 Joule and generate 104 ± 15 Joule, the knee joint absorb 80 ± 3 J and generate 52 ± 8 J, and the hip joint absorb 28 ± 15 J and generate 56 ± 43 J during take-off. One strategy of performance optimization of the long jump take-off therefore should be a minimum of energy loss in the ankle and knee joint and eventually in the MPJ. The net moments at ankle and knee joints, which are quantified to be higher than 300 Nm, provide sufficient tendon force to deform the achilles, the patella and the quadriceps tendons and to store elastic energy. Through energy transfer to the tendon the contractile elements decrease contraction velocity and improve their force potential. The pre-requisite for the energy transfer to the tendons is an appropriate muscle-tendon-unit stiffness at the instant of touchdown which is strongly dependent of the pre-activation of the extensor muscles. Decoupling of foot and shank and therefore a slacking of the Achilles tendon during impact will disturb the energy storage in the Achilles (Brüggemann & Potthast, 2009) and increase the energy loss. This decoupling is depending of the foot-to-ground technique at touchdown for the take-off. Some reported results from isolated one-legged jumps should be transferred to the running long jump take-off. They imply that elastic recoil of tendinous tissue is an important factor determining peak power output and work done about the ankle during the push-off phase in one-legged jumping.

The rapid release of energy from tendons is described in literature as 'catapult action' (Alexander & Bennet-Clark, 1977; Hof, Geelen & van den Berg, 1983). The amount of elastic energy contained by an elastic structure is directly related to elongation of the structure,

while the elongation is determined by the exerted force. Therefore, the energy provided by elastic recoil was stored in a period during which the exerted force inclined. At the beginning of the push-off phase the force is already close to its peak value (Bobbert, Huijing & van Ingen Schenau, 1986). Apparently, storage of energy occurs mainly during the phase of downward movement or eccentric action. Due to the fact that the rate at which energy is released may be much higher than the rate at which it was stored, tendons have been looked upon as power amplifiers (Alexander & Bennet-Clark, 1977). From the findings it appears that during the push-off phase in one-legged jumping peak power output and work done about the ankle reach larger values than power and work produced by the muscle fibers of *m. triceps surae*. This can be attributed to two mechanisms. One of them is elastic recoil of tendinous structures and second is transportation of power from knee to ankle allowing power output and work done about the ankle to reach large values during the push-off phase in one-legged jumping. At first glance these two mechanisms are not supposed to influence the amount of work done externally, which determines the total change of the velocity of the centre of mass. After all, the amount of energy stored in tendons can never be larger than the amount of work done on the tendons and energy transported from knee to ankle may contribute to plantar flexion, but is then no longer available for knee extension.

In addition to the briefly discussed joint movements, joint moments and joint power in the sagittal plane, the ankle joint complex and the knee joint show remarkable movement, joint moments and joint power in the frontal plane during the long jump take-off. The ankle joint receives from the ground reaction forces a powerful external eversion moment, while the knee joint shows a strong external adduction moment. The foot demonstrate a torsional moment which should – in combination with the rearfoot eversion moment - elongate the medial and plantar foot ligaments and store elastic energy. The strong deltoid ligament, the plantar calcaneonavicular (spring) ligament and the long plantar ligament should play an important role in the mechanism to transfer load the ground and proximal segmental acceleration to the more distal body parts.

The role of muscle-tendon units and ligaments in the long jump take-off mechanics underline the relevance and importance of their mechanical properties in terms of tendons' and ligaments' stiffness and energy storage capacity. Only tendons of a sufficient stiffness allow the transmission of the high muscle-tendon forces at the knee and ankle joint without a higher risk of excessive strain and injury. The less compliant tendon allows the storage of a higher amount of elastic energy. Some evidence of higher tendon stiffness in elite athletes in jumping events can be derived from the data presented by Stafiliadis & Arampatzis (2007) on elite and sub-elite sprinters. One can also speculate on a low hysteresis or energy dissipation of tendons as a material property of tendons appropriate for jumping performance. Similar arguments can be used for ligaments especially of the foot of the take-off leg.

ENERGY STORAGE POTENTIAL OF THE HUMAN LEG IN JUMPING: Energy return of human foot and leg during ground contact is often estimated using data from isolated in-vitro or ex-vivo studies published in the literature. However, a determination of the energy return of an intact human leg is complicated. Published data claim the during ground contact of running, the arch of the foot stores and returns 17 J, and that the Achilles tendon stores and returns 35 J (Ker et al., 1987) while the total energy turnover in each stance phase in running was estimated at ~100 J. Ker et al. (1987) reported results from slow, quasi-static tests with human cadavers and interpolated these data to the ground contact of high performance athletes. During ground contact in running or more extreme in jumping the stiffness of the foot will change. For heel or flat-foot landing, the stiffness of the arch is typically less at the beginning of the ground contact and can assumed to become stiffer towards take-off. To assume "one" constant stiffness of the foot arch is probably not appropriate. Furthermore, an estimation of energy storage and return only based on deformation measures and assuming consistent material properties is questionable. Further and more detailed studies of the foot arch during dynamic jumping take-off should figure out the capacity of the dynamic storage and return of energy. Such research should also focus the topic of intervention that reduces the arch deformation through orthotics and the effect on jumping performance.

Estimates for storage of energy in the achilles tendon were 35 J during ground contact in heel-toe running (Ker et al., 1987), 38 J for hopping (Lichtwark & Wilson, 2005) and 16-18 J for drop jumps (Brüggemann, Arampatzis & Komi, 2001). When discussing storage and return of energy, one must take into account that storage and return of energy occur by the entire muscle-tendon complex. Therefore the relevance of energy storage and/or exchange should be discussed considering the whole muscle-tendon system. As reported above the muscle-tendon complex of ankle plantar flexors and knee extensor loose energy during take-off in jumping. The minimization of energy loss was derived as one appropriate concept in performance optimization. From such a standpoint it seems to be logic and appropriate that the energy storage and return concept in the muscle-tendon complex is mainly related to system optimization in terms of guaranteeing an optimal length of the contractile element and a minimum of muscle shortening velocity.

SUMMARY AND CONCLUSION: Long jump performance is up to 90% determined by the flight distance of the athlete's centre of mass. The flight distance depends on four factors of which to take-off velocity and the take-off angle play the dominant role. These variables are strongly related to the approach velocity or the initial kinetic energy of the total body and the vertical and horizontal ground reaction forces. The latter are determined by the accelerations of the swinging leg and the swinging arms, and the net joint moment at the MPJ, the ankle, the knee and the hip joints. MPJ, ankle and knee joint absorb more energy during take-off than they are able to generate. From these observations the concept of minimization of energy loss within the joints was derived. This consideration led to the energy storage and return concept in tendons and – with the given reservation - ligaments of foot, ankle and knee. The potential and efficiency of energy storage and return was critically discussed and mainly reduced to the idea of optimisation of the muscle-tendon complex's function. The role the mechanical properties of muscle-tendon units and ligaments for the long jump take-off mechanics was critically discussed. The relevance and importance of their mechanical properties in terms of tendons' and ligaments' stiffness and energy storage capacity has some evidence of higher tendon stiffness in elite athletes in jumping events. It was also speculated that a low hysteresis or energy dissipation should have an impact to jumping performance.

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