THE DEVELOPMENT OF A MUSCULO-SKELETAL MODEL FOR THE ESTIMATION OF FORCE PRODUCTION AND POWER TRANSFER BY LOWER LIMB MUSCLES DURING EXPLOSIVE EXTENSION MOVEMENTS

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In this study a model with four segment rigid body link system (foot, shank, thigh and trunk) and seven muscles was developed with the purpose of gaining insight on the behaviour of the lower limb muscle-skeletal system during the performance of explosive leg extension movements. Ten elite sprinters performed sprint start movements. The second step after the start was performed over a force platform, and simultaneously, video and electromyography records were obtained. Using an inverse dynamics approach the net moments of force and joint powers of ankle, knee and hip were determined. Considering the physiological cross-sectional area of the muscles and the estimation of effective moment arms, individual muscle forces, muscle moments of force and muscle powers were estimated. The biarticular muscles played a unique role on the movement studied, transferring energy from the proximal to distal joints.

KEY WORDS: muscle-tendon complex, biarticular muscles, power output.

INTRODUCTION: In sport movements, such as sprinting and jumping, the ability to produce explosive leg extension movements is extremely important. Values for maximal knee extension moment of force, calculated by inverse dynamics, are higher than the maximal isometric and isokinetic moments of force values obtained with tests performed on Isokinetic machines. Values of maximal knee extensor moments of force could reach 310 Nm on sub maximal running (Jacobs, Bobbert, & van Ingen Schenau, 1993) and around 500 Nm in drop jump exercises (Bobbert, Huijing, & van Ingen Shenau, 1987a). These values exceed the values for maximal isometric knee extension, around 200 Nm obtained on the classical studies of Wickiewicz, Roy, Powell, Perrine, & Edgerton (1984). One of the mechanisms that might explain these discrepancies is the fact that the biarticular muscles perform differently during actual sports movements than they do on Isokinetic testing. The major difference concerns the length variations of the biarticular muscles. These length changes are dependent on the simultaneous movement of the two joints crossed by the muscle. This means that the force-length and the force-velocity relationships of biarticular leg extensors are different from those obtained during isometric testing, where the adjacent limb is in a fixed position. Another potential influence of the biarticular muscles is the transfer of mechanical power from one joint to the adjacent one, considering the two joints they cross (Prilutsky & Zatsiorsky, 1994). The purpose of this study was to estimate the muscle force production and the transport of mechanical power from hip to knee and from knee to ankle, performed by the rectus femoris (RF) and gastrocnemius (GAS) muscles, during the acceleration phase of sprinting. Additionally the behavior of the triceps surae muscle estimated by the model was compared with the results from direct measured forces on the achilles tendon presented by Komi (1992).

METHODS: Ten elite sprinters (height 1.76±0.04 m, body mass 73.7± 5.1 kg, thigh length 0.433±0.020 m and shank length 0.395±0.018 m) performed 6 sprint starts from blocks. The second stage following the start was performed over a Kistler force platform, and ground reaction forces (GRF) were recorded at 1KHz. The trial where the maximal net horizontal impulse was achieved was selected for analysis. Simultaneously, linear and angular kinematic data from the transversal plane of the ankle, knee, hip and shoulder joints were calculated using a 2D video analysis system (120 Hz) (extension angular movement was defined as positive). After a residual analysis of joint landmarks (Winter, 1990) co-ordinates were filtered with a 10 Hz Hamming window, Butterworth 2nd order, zero phase lag low pass filter. A four-segment rigid body link system was constructed with foot, shank, thigh and HAT (head, arms and trunk). Using an inverse dynamics approach, the net joint forces and moments of force at ankle, knee and hip were calculated (extensor moments of force were defined as positive). GRF were filtered with a 12 Hz low pass filter in order to remove the passive force peaks (van den Bogert & Koning, 1996). The length variation behaviour of thigh and shank muscles was estimated using Visser, Hoogkamer, Bobbert, & Huijing (1991) and Spoor, Leeuwen, C.G.M., Titulaer, & Huson, (1990) polynomials curves fit and the joint angular position. These results were combined with the observed length of thigh and shank of the athletes, estimated using dual frequency x-ray (DXA) images, to obtain the muscle-tendon length variation (Loi) for each athlete. Velocity from origin to insertion (Voi) was calculated by differentiation (dLoi/dt) (concentric velocity was defined as positive). For the same muscles, the effective moment arm equals the derivative of tendon travel with respect to joint angulations (Spoor et al., 1990). On the present model, the calculation of effective moment arm using tendon excursion is acceptable, considering that it is a planar model and that it represents the muscle-tendon unit. Under these conditions was assume that we could not differentiate the patellar tendon force from rectus femoris force. Nevertheless, our model suffers from the limitations expressed by Pandy (1999). These calculations were performed for the following muscles, Gluteus (GM), semi tendinosus (ST), biceps femoris (long) (BF), vastus lateralis (VL), rectus femoris, (RF) gastrocnemius (GAS) and soleus (SOL). Maximal power production was considered to be the objective for the extensor muscles and assuming that a reciprocal inhibition control system was predominant (Prilutsky & Zatsiorsky, 1994). The physiological cross-sectional area (PCSA) values presented by Roy & Edgerton (1993) were used to calculate specific dynamic muscles tension for the studied muscles. Assuming that: muscle tension is proportional to PCSA and that mono-articular antagonists are inactive, dynamic muscle tension was calculated (Winter, 1990): Individual musculotendon unit force was calculated by multiplying dynamic tension of a muscle, or muscle group and the PCSA of this muscle or muscle group (Winter, 1990). Muscle power was obtained by multiplying muscle force by the instantaneous rate of change of its length (V_{oi}). Mechanical power transferred from hip to knee by RF ($P_{transp.RF}$) equals the difference between knee net power and the knee extensors muscles power, the same occurs for knee to ankle joint. The amount of power transported by GAS ($P_{transp.GAS}$) from knee to ankle (or the opposite) equals the difference between ankle net joint power and plantar flexor power (Prilutsky & Zatsiorsky, 1994). The proposed model presents some important limitations: thus not takes into account the architectural structure of muscle fiber, as well as muscle fibers composition and especially does not differentiate muscle fibers from tendon fiber. The model estimates the behavior of the muscle-tendon complex and do not predict muscle fibers force. Additionally this algorithm leads to an absence of co-activation of hamstrings (HA) and rectus femoris and the model does not predict the hamstrings knee moment of force. Other limitations of the model are that muscle composition is not accounted for. As GAS presents a higher percentage of fast twitch fibers in comparison with SOL, this model most probably tends to overestimate SOL contribution for triceps surae force and underestimate GAS.

RESULTS AND DISCUSSION: The transfer action or tendon action of biarticular rectus femoris and gastrocnemius was estimated by comparing the net joint power for each joint and the muscle power. The difference obtained for each joint represents the amount of energy transferred by the biarticular muscles from a joint to its adjacent. The method used presents the advantage of allowing internal verification, because the total net joint power should be of the same amount as the total muscle power. On the top left graph of Figure 1 it can be observed that the two curves are very similar indicating that the energy balance was obtained. The transfer action of the biarticular muscles is seen clearly on Figure 1, from hip to the knee joint and from the knee joint to the ankle joint (on both knee and ankle joints joint power exceeds muscle power while on the hip joint muscle power exceeds joint power). The transfer action of RF and GAS during the early phase of support is small indicating that during the early sprint acceleration the absorption phase characteristic of running is absent, except for the ankle, and apparently with small transfer of power from ankle to knee. After 45% of support phase, where leg extension is predominant RF and Gas are able to transfer energy from the hip extensors to the knee and from the knee extensors to the ankle joint. The mechanical energy transferred was calculated integrating over time the transfer power curves showed on Figure. 1. The energy transferred by RF from hip to knee, present a mean value of 35.63 J, which represents 21.2 % of the knee energy. The transfer of energy from knee to ankle performed by GAS achieves a mean value of 22 J being 23.6 % of the total work performed on this joint.

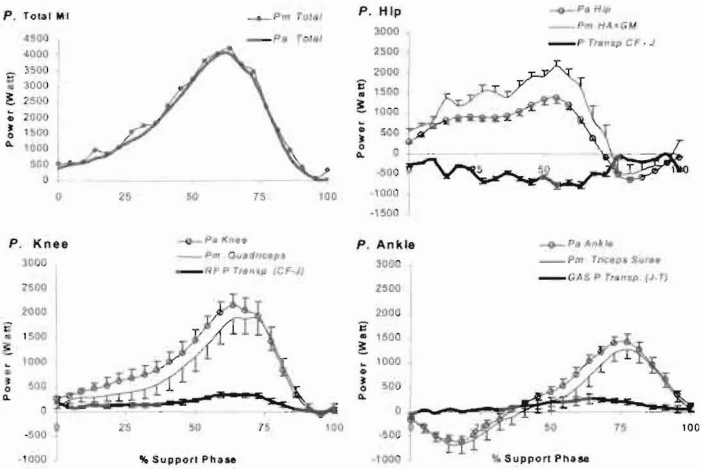

Figure 1. Average curves (n=10) after time normalization for 100% of the support phase, vertical bars over the curves represented standard deviation. Net joint power for hip, ankle and knee, (P Ankle, P Knee and P Hip), mean curves for muscle power (P Triceps, P Quadriceps and P HA + GM) and power transfer by biarticular muscles RF and GAS, from hip to knee and from knee to ankle respectively (RF P Transp and GAS P Transp). The graphic on the top represents total muscle power and the total joint power for the lower limb (the similarity between this two curves indicate the internal coherence of the model.

These results are in close agreement with those presented by Jacobs, Bobbert, & van Ingen Schenau (1996), and Bobbert, Huijing, & van Ingen Schenau (1987b) for sprint start and vertical jumping. The present results are similar to the values presented by Prilutsky & Zatsiorsky (1994) for vertical jumping using a model similar to the one used in the present study. Figure 2 represents the force length and force velocity curves obtained for the acceleration phase of the sprint start. The force length curve clearly shows a positive work loop indicating that the energy accumulated on the muscle-tendon complex during the eccentric phase is recoiled during the concentric contraction. The force velocity curve presents a concave shape reinforcing the idea of the utilization of elastic energy during the eccentric phase as an instantaneous force amplification factor.

CONCLUSION: The musculo-skeletal model proposed allowed the estimation of the behaviour of the muscle-tendon complex during an actual sport movement performed characterized by the generation of maximal leg extension power, the second stance period after sprint start from blocks. The similarity between the total sum of joint net powers at the lower extremity and the sum of the total power of all the muscles of the lower limb indicates the adequacy of the model. The biarticular muscles appear to have an important role in transferring energy from the proximal joint, where the muscles with larger volume are located, to the distal joints. This transfer action could be partially responsible for the discrepancy between max isometric moment of force registered on dynamometer and the net moment of force values calculated by inverse dynamics on actual sport movements. Additionally, the analysis of the force-velocity curve (Fm-Voi) shows a clear concave shape of the curve that contrasts with the traditional (Fm-Voi) obtained on studies in vitro with isolated muscle fibers. The differences obtained have important meaning, for instance the maximal power in isolated muscles was obtained at 30 % of max contraction velocity while in freely moving situation max power could be obtained at 60 % of maximal force and at 80 % of maximal contraction velocity. This force-velocity relation found in actual movements studies appears to be connected with elastic behavior of the muscle-tendon complex. The ability to maintain high levels of stretch reflex during the early eccentric phase, and a strategy of the neuromuscular system to reset the motoneurons in order to produce a triggered and synchronized activation of all motor units, simultaneously with the ground contact, could also play an important role. The mechanisms listed above should be responsible for the higher moments of force obtained on the inverse dynamics analysis of actual dynamical movements. These findings should be taken into consideration when isometric or isokinetic tests are used to evaluate power athletes.

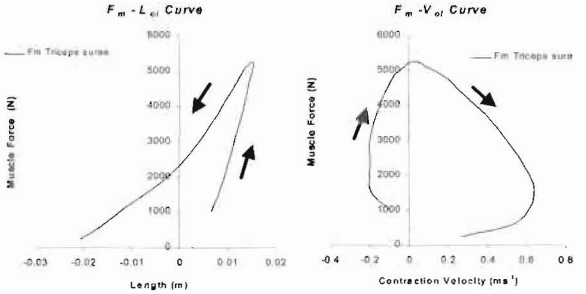

Figure 2. Force length and force velocity curve estimated for the triceps surae muscle-tendon complex. Average curves (n=10) after time normalization for 100% of the support phase.

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