ESTIMATION OF POWER OUTPUT FROM LEG EXTENSOR MUSCLES IN THE ACCELERATION PHASE OF THE SPRINT

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The purpose of this study was to estimate the transfer of mechanical power from hip to knee, and from knee to ankle, performed by the RF and GAS muscles during the acceleration phase of sprinting. The energy transfer was estimated using a muscular skeletal model. The energy transferred by RF from hip to knee during the push off phase was 72.6±14.5 J (34.4±5.5 % of net knee joint work) and the transfer of energy by GAS from knee to ankle was 23.3±3.6 J (24.9±7.3 % of net ankle joint work). This energy transfer allows high power output on the more distal joint, and could provide a partial explanation of why the moments of force on actual explosive sport movements exceed the values obtained in an isometric test.

KEY WORDS: biarticular muscles, energy transfer, muscular skeletal model

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) or those presented by (Cabri, 1989) who presented a value of 357 Nm, for average maximal isometric knee extensor moments. The same discrepant behaviour was found for plantar flexion (Bobbert, 1988).
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 biarticular muscles is the transfer of mechanical power from one joint to the adjacent one, considering where the two joints they cross (Prilutsky & Zatsiorsky, 1994).
The purpose of this study was to estimate the transport of mechanical power from hip to knee and from knee to ankle, performed by rectus femoris (RF) and gastrocnemius (GAS) muscles, during the acceleration phase of sprinting. This power transport action partially explained the difference found on the moment of force between maximal isometric testing and the value obtained by inverse dynamic on this explosive leg extension movement.

METHODS: Ten elite sprinters (height 1.761±0.042 m, body mass 73.7± 5.1 kg, thigh length 0.433±0.020 m and shank length 0.395±0.018 m) were tested for maximal isometric knee extension and ankle plantar flexion on a biodex isokinetic machine. The isometric test was performed at the angle where each athlete reached his highest isokinetic moment of force, when performing the maximal isokinetic test at low velocity (30 degree per second).
The same sprinters 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 4 order, 0 phase lag low pass filter. The residual signal amplitude was less than 5 mm (RMS) for all the markers (Winter, 1990). 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 17 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 (Visser, Hoogkamer, Bobbert, & Huijing, 1991) and Grieve et al. 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 (L_{oi}) for each athlete. Velocity from origin to insertion (V_{oi}) was calculated by differentiation (dL_{oi}/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, Leeuwen, C.G.M., Titulaer, & Huson, 1990):

Considering:

$F\,ds = \mathrm{M_f}\,d\theta$ Then the effective moment arm: $a = \mathrm{M_f}/F = ds/d\theta$ **(eq.1)**

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). A physiological criteria was use to estimate force distribution among muscles, the physiological cross-sectional area (PCSA) values presented by Roy and Edgerton (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):

$$\text{Joint } \mathrm{M_f} = \sum_{i=1}^{n-muscles} PCSA_i \times m.tension_{(t)} \times d_{(arm)i(t)} \qquad \textbf{(eq.2)}$$

with:

Joint $\mathrm{M_f}$ - *Joint net moment of force,* $PCSA_i$ *- physiological cross-sectional area of the i muscle,* $m.tension_{(t)}$ *- dynamic tension at the instant t,* $d_{(arm)\,i\,(t)}$ *- instantaneous moment arm of muscle i at the instant t.*

These calculations must be performed in the following order:

a) First, the forces of the ankles extensors are calculated, (eq. 2) following that, the moment of force produce by the biarticular GAS is subtracted from the knee net moment, note that on our definition flexor moments are negative. So, in the knee moment of force Joint $\mathrm{M_{f\,(knee)}}$ the value of the flexor moment of force produced by GAS is included (eq. 3).

b) Second, the forces of knee extensors are calculated (eq. 3) following that the flexor moment of force produced by the RF on the hip joint is calculated and subtracted from the net hip moment of force (eq. 3).

$$\text{Muscle force}_{i\,\text{(knee extensor)}\,(t)} = \frac{\left(\text{Joint.}\mathrm{M_{f\,(knee)}} - \text{GAS } \mathrm{M_{f\,(knee)}}\right)}{\sum_{i=1}^{n} PCSA_i \times d_{(arm)i(t)}} \qquad \textbf{(eq.3)}$$

with:

Muscle force $_{i\,\text{(knee extensor)}\,(t)}$ – *Tension on the i knee extensor*, Joint $\mathrm{M_{f\,(knee)}}$ – *Knee joint net moment of force,* GAS $\mathrm{M_{f\,(knee)}}$ - *GAS knee moment of force*, $PCSA_i$ *- physiological cross-sectional area of the i muscle,* $tension_{(t)}$ *– dynamic tension at the instant t,* $d_{(arm)\,i\,(t)}$ *- instantaneous moment arm of muscle i at the instant t.*

Individual muscle 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 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 the plantar flexor (Prilutsky & Zatsiorsky, 1994).
It is important to note that this algorithm leads to an absence of co-activation of hamstrings (HA) and rectus femoris. This 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, probably this model tends to overestimate SOL contribution for triceps surae force and underestimate GAS.

RESULTS: Table 1 summarised the results for the isometric peak moment of force for knee extension and ankle plantar flexion in comparison with the peak values registered from inverse dynamics on the leg extension action that characterised the acceleration phase of sprint start. The values obtained for the actual sport movement were consistently higher than those obtained on isometric knee and ankle extensions. Although there are several other mechanisms that could explain these results, such as neural inhibition, reflex potentiation or elastic enhancement, the present study is only concerned with power transfer performed by biarticular muscles.

Table 1 **Average Results for the Knee and Ankle Maximum Moment of force on a isometric tests on the biodex system3 machine, and for maximum knee extension moments during the push-off phase of the second support phase after sprint start from blocks. This means that the Inverse dynamics moments of force were obtained during concentric contraction of plantar flexors and knee extensors**

Average results (N=10)	Isometric M_f (Nm)	Inverse dynamics (Nm)
Knee extension	303.3 ± 43.4	399.2 ± 21.3
Plantar Flexion	177.8 ± 28.7	237.7 ± 15.1

Figure 1 A, B and C present the mean curves from the 10 sprinters after time normalization to 100 % of support phase. Figure 1A show the net joint moments of force for the three leg joints, a clear proximal to distal synchronization is evident. During the first half of the support phase hip joint generates high power, while knee joint muscles were acting isometricallly and the ankle extensors were acting eccentrically. Probably the hip joint is absorbing part of the passive moment generated by the GRF on the ankle and also rotating the upper body. The isometric behaviour of the knee joint allows the rotation of the body around the ankle joint. The first half of the support is characterised by predominance on rotation of the CG around the centre of pressure (Jacobs & van Ingen Schenau, 1992). After 45% of the support the knee and ankle muscles generate increasingly higher power, which allows an explosive extension of the leg. The knee peak power occurs around 73 % of the support and peak power of the plantar flexors takes place near 85% of this phase.

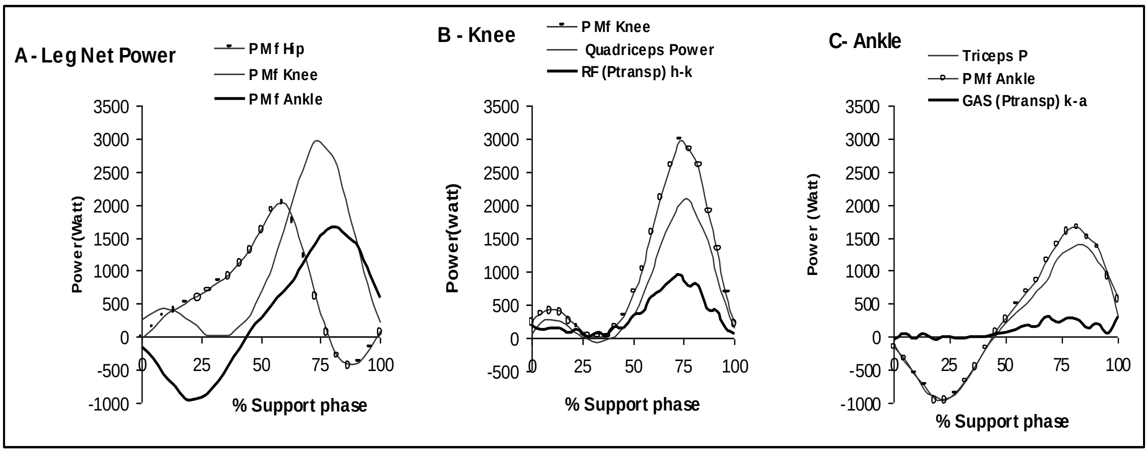

Figure 1- Average curves (n=10) after time normalization for 100% of the support phase, for reason of clarity the SD is absent. Fig.1 A present the net joint power for hip, ankle and knee. Fig 1B and 1C show the mean. curves for net joint power, muscle power, and power transfer by biarticular muscles RF and GAS respectively

The transfer action of the biarticular muscles is seen clearly on Fig. 1B for the knee joint and 1C for the ankle joint. 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 no power transfer from ankle to knee (Table 2). 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 Fig. 1 B and C. The energy transferred by RF from Hip to knee, present a mean value of 72.6 J, which represents 34.4 % of the Knee energy. The transfer of energy from knee to ankle performed by GAS achieves a mean value of 23 J being 24.9 % of the total work performed on this joint.

Table 2 **Average results (n=10) for the transport of mechanical energy from ankle to knee Work (-) Gas representing the shock absorbing. Transport of mechanical energy from Knee to ankle Work (+) GAS and from hip to knee Work (+) RF during the push-off phase**

Work (-) Mf ankle (Joule)	Work (-) GAS transported ankle to knee	% W transported
-39.6±7.8	0.14±0.04	-0.36±0. 10
Work (+) Mf ankle (Joule)	Work (+) GAS transported knee to ankle	% W transported
112.2±9.1	23.3±3.6	20.6±7.3
Work (+) Mf Knee (Joule)	Work (+) RF transported Hip to knee	% W transported
210.9±16.2	72.6±14.5	34.4±5.5

These results are in close agreement with those presented by (Jacobs, Bobbert, & van Ingen Schenau, 1996), (Bobbert, Huijing, & van Ingen Schenau, 1987b) for sprint start and vertical jumping. They used a direct dynamics model. 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.

CONCLUSION: 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. The distal limbs have muscles with shorter fibres and larger tendons that are suitable for fast contracting velocities that are associated with the transfer mechanism of the biarticular muscles allowing for an efficient high power output at 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. These findings should be taking into consideration when isometric tests are used to evaluate power athletes.

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