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UNDERSTANDING MUSCLE PROPERTIES IN SPORTS PERFORMANCE OPTIMIZATION

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Understanding muscle properties in the context of sports movements is crucial for maximizing power output, minimizing the cost of transport, or delaying fatigue. Here, we review the three basic properties of skeletal muscles that affect optimal working performance: the force-length, the force (power)-velocity, and the time-dependent force properties. We demonstrate on two examples (cycling and cross-country skiing) how knowledge of muscle properties can help maximize sport performance.

KEY WORDS: Skeletal muscle, force-length relationship, force-velocity relationship, residual force enhancement (depression), sprint cycling, cross-country skiing, muscle mechanics, performance optimization

INTRODUCTION: The capacity of muscles to produce high amounts of work in a short period of time often determines success in sports. It is mechanically speaking the average power and, for a muscle, can be determined as the force of the muscle multiplied by its speed of shortening, thereby tacitly assuming that the muscle force vector and the displacement of the muscle attachment points are collinear. The instantaneous power that can be generated by a muscle depends on the muscle's instantaneous lengths, its speed of shortening, and its contractile history.
The muscle's optimal length for maximum power output is given by the force-length relationship and corresponds to the plateau of this curve (Figure 1). On the molecular level, the plateau of the force-length relationship is thought to occur when actin-myosin filament overlap is maximal, and thus sarcomere length is optimal (Gordon et al., 1966). When stretched beyond the plateau, force decreases because of the loss of overlap between actin and myosin filaments and the associated loss of probable cross-bridge interactions (Huxley, 1957). When shortened below the plateau, myofilament interference, loss of activation, internal resistance and other factors are thought to contribute to a muscle's loss of force.

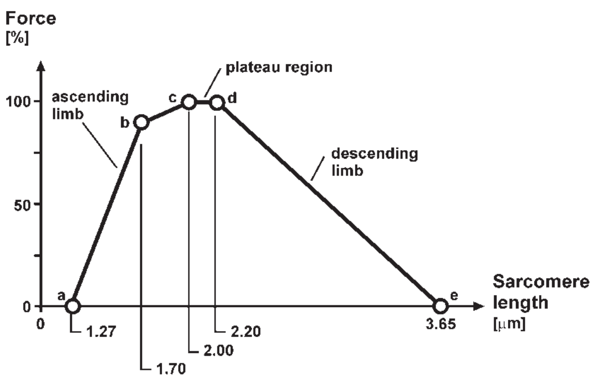

Figure 1: Sarcomere force-length relationship for frog skeletal muscles. Note the plateau of the relationship between 2 - 2.2 μm, which corresponds to maximal overlap of actin and myosin filaments in frog muscles.

A muscle's optimal speed of shortening for maximal instantaneous power output is given by the shape of the force-velocity relationship (Hill, 1938) and corresponds, under normal circumstances, to about 30-35% of the maximal (unloaded) speed of shortening of a muscle (Figure 2). It has been argued in the animal world, that maximal power output is obtained by optimal speed of muscle shortening that is maintained throughout the movement, as for example in the incredible performances in frogs' jumping (Lutz & Rome, 1993). Also, for human cyclists, it has been shown in laboratory experiments that the optimal cadence of pedaling for maximizing power output corresponds to approximately 120 revolutions per minute. It has been thought that this pedaling frequency optimizes power output of the major limb extensor muscles which power the pedals during cycling.

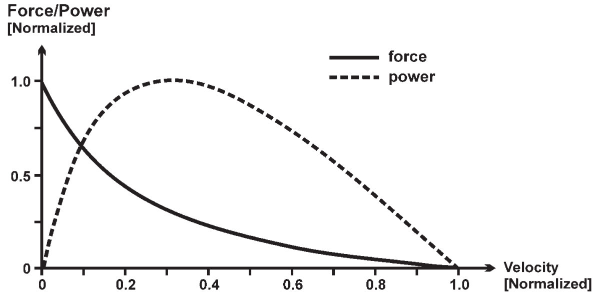

Figure 2: Force-velocity and power-velocity relationship for skeletal muscles. Note that the maximal power output occurs at a speed of shortening of approximately 30-35% of the maximal speed of shortening obtained in the unloaded muscle.

Finally, power output of a muscle can be enhanced when shortening of a muscle is preceded by active stretching. Aside from the benefits of increased force during stretching, the possible storage of elastic energy during stretching and the low energetic cost of muscle force during stretching, it has been shown that active stretching of muscles results in a long-lasting increase in force that has an active and passive component (Herzog & Leonard, 2002), that can be utilized during the following shortening contractions (Edman et al., 1982). This so-called residual force enhancement is increased with increasing stretch magnitude and increasing muscle lengths, at least in a first approximation (Figure 3). Therefore, power output in sport activities might be enhanced and performance might be maximized by using muscles such that they work at lengths close to the plateau of the force-length relationship, shorten close to about 1/3 of their unloaded speed of shortening and are preceded by active stretches.

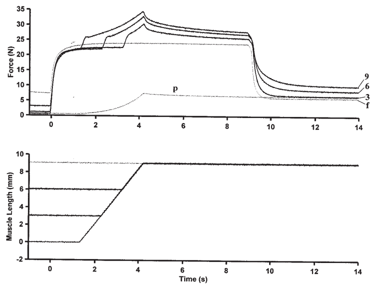

Figure 3: Force enhancement following active stretching of skeletal muscle increases with increasing magnitude of stretch (at least to a first approximation). Note that the steady state isometric forces following active stretching of 3, 6, and 9mm are higher than the corresponding isometric force for the purely isometric reference contraction. Cat soleus at 35° C

METHODS: We studied cycling and cross-country skiing in view of existing muscle properties and attempted to draw conclusions on optimal performance characteristic in these two sports based on muscle mechanical considerations. For cycling, this was achieved using a theoretical musculoskeletal model of the lower limb, measurements of cycling performance and determination of the lower limbs' force-length and force-velocity properties for a variety of activation levels.

For cross-country skiing, we measured the oxygen uptake for skiers traveling at 6-33km/h on a motor driven treadmill using the one-skate and the two-skate techniques. We then compared the cost of transport at given speeds for the one- and two-skate techniques and analyzed the forward impulses provided by poles and skis, and evaluated them within the frame work of the arms and legs muscular properties.

RESULTS: For cycling, we found that at optimal power output, individual muscle properties were not optimal (Yoshihuku & Herzog, 1990; Yoshihuku & Herzog, 1996). Furthermore, we demonstrated theoretically that cycling power could be increased by changing the geometry of the pedal path and by disengaging the strict 180° offset of the pedals. Most importantly, however, we confirmed that the force-length properties of the leg extensor muscles could be optimized by adjusting the seat height and that, once adjusted to the optimal height for maximal power output, optimum was retained for sub-maximal cycling conditions, because the elongation of muscle fibres due to decreased force at sub-maximal efforts was compensated for by an activation-dependent shift in the plateau of the force-length relationship of the knee extensor muscles (Austin et al., 2010).

For cross-country skiing, we found that the cost of transport was lower for the two-skate technique at very low and very high speeds of skiing, while the cost of transport was lower for the one-skate technique at intermediate speeds that would contain the speeds used for a typical long-distance race (Figure 4). This surprising, and completely unique result in "four-legged" locomotion, can be explained with the muscle properties of the arms powering the poles and the legs powering the skis.

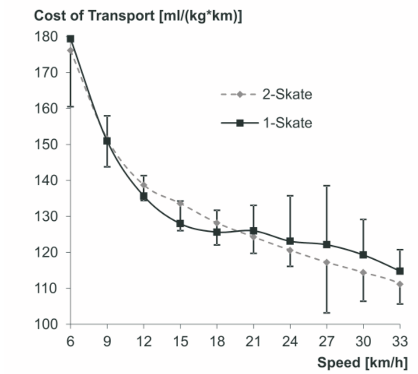

Figure 4: Cost of transport as a function of the speed for the one-skate and two-skate techniques in cross-country skiing. Note that the cost of transport curves intersect twice (at about 9 an about 20km/h) indicating that it is more economic to ski with the two-skate technique at very slow (<9km/h) and very high (>20km/h) speeds, while the one-skate technique seems to be most economical for intermediate speeds (9-20km/h).

CONCLUSION: Knowing muscle properties for target movements is crucial for optimizing power output and work performance in sports. Specifically, proper bike geometry, pedal length, and gear ratio, are crucial for maximizing power output in cycling, while proper gait selection in cross-country skiing minimizes cost of transport.

REFERENCES:

Austin, N., Nilwik, R., & Herzog, W. (2010). In vivo operational fascicle lengths of vastus lateralis during sub-maximal and maximal cycling. *J Biomech., 43,* 2394-2399.

Edman, K. A. P., Elzinga, G., & Noble, M. I. M. (1982). Residual force enhancement after stretch of contracting frog single muscle fibers. *Journal of General Physiology, 80,* 769-784.

Gordon, A. M., Huxley, A. F., & Julian, F. J. (1966). The variation in isometric tension with sarcomere length in vertebrate muscle fibres. *Journal of Physiology (London), 184,* 170-192.

Herzog, W. & Leonard, T. R. (2002). Force enhancement following stretching of skeletal muscle: a new mechanism. *Journal of Experimental Biology, 205,* 1275-1283.

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society London, 126,* 136-195.

Huxley, A. F. (1957). Muscle structure and theories of contraction. *Progress in Biophysics and Biophysical Chemistry, 7,* 255-318.

Lutz, G. J. & Rome, L. C. (1993). Built for jumping: The design of the frog muscular system. *Science, 263,* 370-372.

Yoshihuku, Y. & Herzog, W. (1990). Optimal design parameters of the bicycle-rider system for maximal muscle power output. *Journal of Biomechanics, 23,* 1069-1079.

Yoshihuku, Y. & Herzog, W. (1996). Maximal muscle power output in bicycling as a function of rider position, rate of pedalling and definition of muscle length. *Journal of Sports Sciences, 14,* 139-157.