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CAN MUSCLE ACTIONS (WORK) CALCULATED BY A MUSCULOSKELETAL MODEL EXPLAIN RUNNING ECONOMY?

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The purpose of this study was to relate mechanical parameters, muscular activity and measured running economy (RE) during treadmill running to muscular work derived from a musculoskeletal model. Participants were tested in three systematically modulated shoes. Methods: Subjects performed three trials in one testing session. Each session consisted of 16 min running on a treadmill, in each of the three modified shoes at a constant running speed (lateral wedge, neutral and medial wedge under the heel of running shoe). A VO_2 analyser system was used to monitor oxygen consumption. Sagittal plane and rearfoot kinematics were assessed using 3D high-speed video system and a rearfoot goniometer. Muscle activations were recorded using bipolar surface EMG on eight muscles of the right leg. Results: Oxygen consumption was not significantly changed by inserts. However, muscle activity of soleus, tibialis anterior and biceps femoris were increased for the lateral insert. While model calculations reflected the measured changes in individual muscles the overall work did only partly reflect the measured metabolic energy.

KEY WORDS: musculoskeletal model; Running Economy; Kinematics; Rear foot movement;

INTRODUCTION: Running economy (RE) is typically defined as the metabolic energy demand for a given velocity of submaximal running, and is determined by measuring the steady-state consumption of oxygen (VO_2) and the respiratory exchange ratio (Saunders, Pyne, Telford, & Hawley, 2004a). Independent from that observation a detailed mechanical analysis of running technique using an individualized musculoskeletal model should be able to explain the influence of running technique on RE and on performance.

It seems that minimizing the external vertical and horizontal forces during running may enhance running economy. Reducing vertical forces might influence the stride length and frequency, whereas reductions in horizontal peak forces might be an object for a motor skill approach. Therefore, runners were advised to minimize the vertical movement of the centre of gravity and the horizontal braking in each running step to improve running economy and distance running performance (Støren, Helgerud, & Hoff, 2011).

At a different level, muscle activity may be modulated by variations in running shoes which would make it likely that this will influence fatigue during longer training sessions. Increased neuromuscular effort (Moritani et al, 1993) should then accompany greater energy consumption during steady state running. Other authors (Derrick et al, 2002) found knee flexion at heel impact increased and the rear foot becoming more inverted at impact with increased exhaustion during running. Modifications in midsole geometry to vary rear foot movement were used on trained subjects who performed 12.5 km runs with each shoe modification respectively (Kersting & Newman, 2003). Impact forces and rearfoot motion did not follow predicted values from previous studies (Stacoff et al., 1988).

Mechanical/numerical models of the body, can provide detailed information about the state of every element of the model, and would allow investigation of the role of each elastic element in the system as well (Rasmussen & Damsgaard, 2000). The musculoskeletal systems of humans and animals are mechanically very complex and computational models must be highly simplified in order to be reasonably efficient. Typically, the musculoskeletal system is assumed to be a rigid-body system allowing for standard methods of multibody dynamics to be applied. AnyBody is capable of analysing the musculoskeletal system of humans or other creatures as rigid-body systems. In addition, the model must have reasonable representations

of the muscle geometry and the recruitment pattern of the muscles, which are both complicated issues. The muscles consist of soft tissue and they wrap about each other and the bones, ligaments, and other anatomical elements in a complicated fashion. Reasonable modelling of these geometries is essential for the mechanical model.
AnyBody is a general software system for simulation of human movement. Models are constructed from bones; joints, muscles and tendons, and smaller or larger subsets of the body can be modelled and analysed. The system is based on inverse dynamics and solves the redundancy problem by means of a minimum fatigue criterion that can be cast into the form of a linear programming problem (Rasmussen & Damsgaard, 2000), providing the system with a very high numerical efficiency allowing moving models involving hundreds of muscles.
The AnyBody Modeling System, based on so-called inverse-inverse dynamics and a minimum fatigue criterion for muscle recruitment, simplifies the modeling and simulation of the human body significantly, and this paves the way for a numerical investigation of energy cost and metabolism during running and movement.
The purpose of this study was to explain mechanical parameters and muscular activity affecting running economy (RE) by a musculoskeletal model (AnyBody) during treadmill running in three systematically modulated shoes.

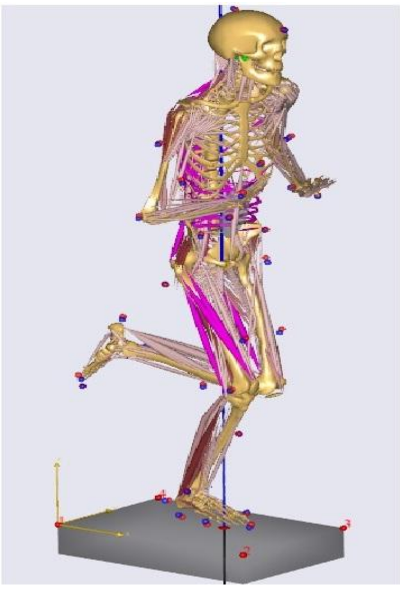
Figure1 Running Model in AnyBody

METHODS: Ethical approval was obtained from the university's Human Ethics Committee. Experienced, sub-elite runners were recruited and allowed for a 5-10 min warm up to allow familiarization with treadmill running. Following the warm-up, each subject performed three trials in one testing session. Each session consisted of 16 min running on a treadmill (Quinton) at about 80% of their individual 5000-m time, in each of the three modified shoes (lateral wedge, neutral and medial wedge under the heel of a Nike Pegasus running shoe). A VO_2 analyzer system (MOXUS Modular VO_2 System) was used to monitor oxygen consumption.
Muscle activations were recorded using bipolar surface EMG on eight muscles of the right leg (Biovision). Muscle activity was filtered, rectified and integrated over the whole step cycle as well as the average pre-activation 50 ms prior to ground contact calculated. Sagittal plane and rear foot kinematics were assessed using a 2D high-speed video system (Simi-Motion, Basler AF602 camera) with reflective markers placed on the shoes and the right leg, and a custom-made rear foot goniometer, respectively. In a second data collection session 10 trials of each runner were collected during overground running over a force platform in a laboratory with 3D kinematic data collected for the whole body using an eight-camera movement capture system (EVa V3.2, Motion Analysis Corp., USA).
Kinematic data were assessed by a musculoskeletal model (AnyBody 5, AnyBodyTech, DK) providing results for muscle activity based on inverse dynamics combined with an optimization method. A simple estimate of metabolic cost based on muscle power in relation to eccentric and concentric work. These individual muscle powers are summed over all muscles in the model (Figure1).
A repeated measures ANOVA was used to test for significant differences ($p<0.05$).

RESULTS: Rearfoot movement was systematically altered showing a maximum eversion of 6.1 +/- 1.8 deg for medial, 9.3 +/- 2.0 deg for neutral and 10.6 +/- 1.9 deg for lateral inserts. Measured muscle activity was systematically varied for some muscles of the leg, i.e., the

tibialis anterior and soleus with lower activity for the medial insert (Figure 2). A similar ranking was observed for the soleus muscle force integral while the tibialis activity showed constant values across trials.
Running Economy was significantly greater ($p < 0.05$) in the medial wedge under the heel condition as compared to the lateral wedge and neutral condition. The calculated total muscle work done per cycle was greatest for the lateral wedge which is opposed to the physiological measure of RE.

Table 1) Muscle Activity (Soleus and Tibialis Anterior) integrated muscle force vesus running economy (RE) versus summed metabolic cost (SMC) from model calculations.

	Experimental Measures			Musculoskeletal Modeling		
	Medial	**Neutral**	**Lateral**	**Medial**	**Neutral**	**Lateral**
Soleus (% - N/kg*s)	87.7	100	104.3	0.3971	0.3973	0.6372
Tibialis Ant. (% - N/kg*s)	89.2	100	109.0	0.1132	0.0899	0.1129
RE (m/kg/ml) / SMC (arb. Units)	3.635	3.564	3.527	1477	1602	967

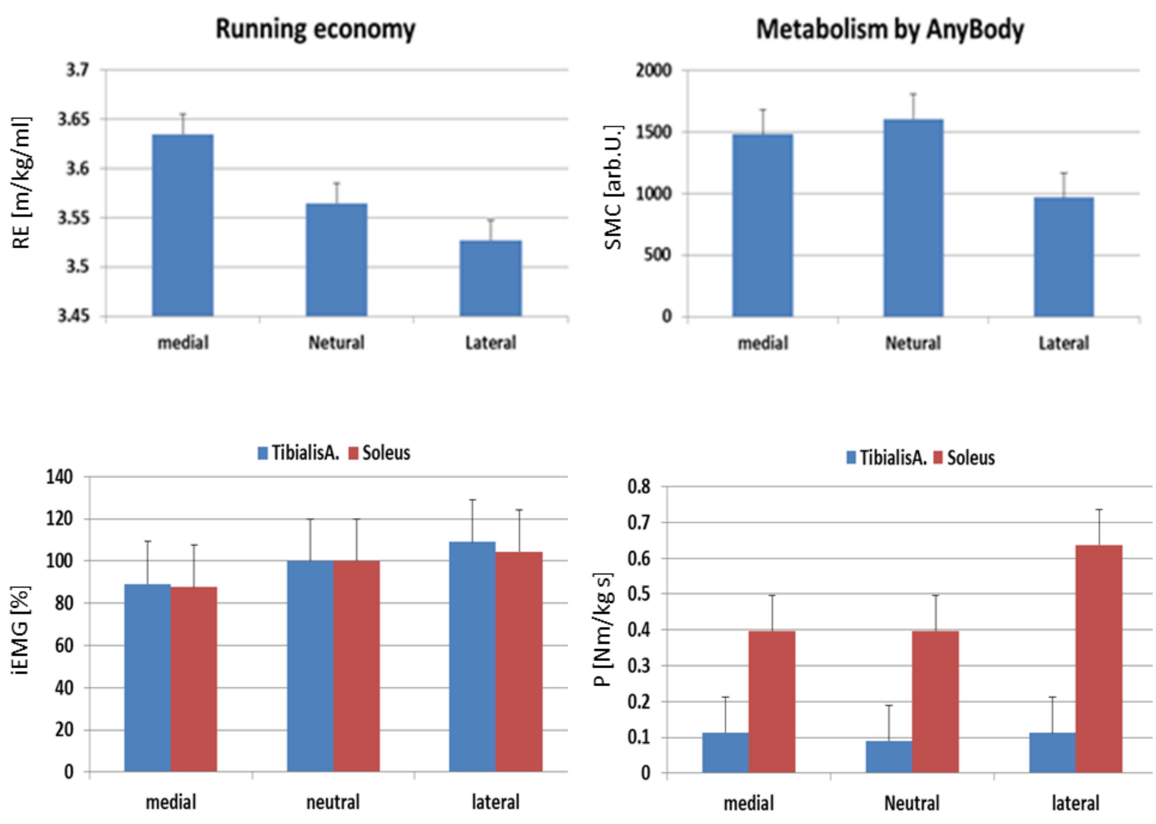

Figure 2: Running economy versus metabolism and muscle activity. Left graphs show experimental results, right graphs are modeling results.

DISCUSSION:
Measured muscle activity showed a systematic variation with rearfoot movement changes indicating a lower muscular effort for muscle involved in guiding initial foot contact (TA) and muscles stabilizing the ankle joint during push-off (SO). The modeling results point into a similar direction for the soleus, however, the alterations are not as systematic as for the EMG

measures. The tibialis results show only minimal variations across conditions. This is not necessarily surprising as TA is mostly active during the swing phase just prior to foot contact in preparation of the heel contact. This preparative activation is not detectable by inverse dynamics calculations as muscle activity is only required during contact. There is no preactivation required outside the ground contact phase. The soleus is acting during push-off and mirrors to a certain extent the measured changes. In summary it may be speculated that a medial insert is more economical when used by runners with normal feet. This may change if runner populations with supinated or pronated feet are tested. Thus such steady state measures of muscle activity may allow to determine the optimal footwear for certain runners. If model calculations could be further validated such an approach may serve to further optimize footwear or running technique respectively.

The metabolic alterations observed in this study are minimal and show no significant differences between inserts. However, there is an order in these results which may imply that lateral shoes are less effective which would match the neuromuscular effort changes of certain muscles.

The model based estimates of total body metabolic cost do not match the order of the differences shown for the physiologic measures. Also the magnitudes of change are substantial which is in contradiction to the small differences measured. It has to be noted that the estimates were only calculated for the ground contact phase as preactivation is not realistically included in the modeling approach. It might well be that the preparative muscle activations as well as running technique alterations during swing have a considerable effect. Second, the muscle power calculation in this model is based on a very simple linear factor relating muscle work to metabolic energy demand. Further model improvements may be required to fully model metabolic cost of a runner.

CONCLUSION: Based on simulation output, metabolic muscle work and running efficiency were computed. A simulation study of this kind may increase the understanding about biomechanical parameters effect on running economy and its relationship to metabolism

The results indicate that, we have reasonable relationship between simulation and muscle activations. However, whole body muscle work predictions seem not to be possible with the current model.

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