

EXPLORING THE POTENTIAL EFFECTS OF STRENGTH TRAINING ON RUNNING ECONOMY: A SIMULATION STUDY

Aaron S. Fox¹, Danielle Trowell^{1,2} and Jason Bonacci¹

Centre for Sports Research, Deakin University, Melbourne, Australia¹
Australian Institute of Sport, Canberra, Australia²

Strength training can improve running economy (RE) and performance in distance runners. This study investigated the effect of potential adaptations stemming from strength training on RE using simulation. Muscle-tendon unit (MTU) properties (muscle strength and mass, pennation angle, tendon stiffness, fibre composition) of muscle groups were altered within muscle-driven simulations of running at 4.5 and 6.5 m·s⁻¹. Outputs from the muscle-driven simulations were input to an energetics model to determine whole-body metabolic power. Alterations to MTU properties resulted in variable changes (range = 1.4% decrement – 8.9% improvement in RE) to whole-body metabolic power and RE. The findings highlight potential targets for strength training programs aiming to improve RE in distance runners.

KEYWORDS: distance running, modelling, muscle, energetics.

INTRODUCTION: Running economy (RE) (i.e. energetic cost relative to body mass) is a strong predictor of endurance performance for distance runners (Bassett & Howley, 2000). Strength training (e.g. maximal-, hypertrophy- and reactive-strength training) has been shown to improve RE, with improvements in time-trial results also observed (Denadai, de Aguiar, de Lima, Greco, & Caputo, 2017; Paavolainen, Häkkinen, Hämmäläinen, Nummela, & Rusko, 1999). The wide calibre of participants, variable forms of strength training used, and relative training loads prescribed across the literature makes it difficult to determine the specific neuromuscular or musculoskeletal adaptations contributing to improved RE and performance. Understanding how specific adaptations affect RE may lead to improved training programs for distance runners. The purpose of this study was to investigate the effect of potential adaptations stemming from strength training on RE within a simulation framework.

METHODS: One male with experience in distance running (age = 27 yr; height = 1.71 m; mass = 72.3 kg) was used as the participant for this study. Three-dimensional (3D) kinematic and kinetic data of the lower limb and torso were collected during treadmill running at two separate speeds (4.5 m·s⁻¹ and 6.5 m·s⁻¹). Marker trajectory data were collected using a 3D motion capture system (250Hz; Vicon, Oxford Metrics Limited, Oxford, United Kingdom). Markers were placed on the torso and lower limbs in accordance with a previously established model (McLean, Su, & van den Bogert, 2003). Synchronised ground reaction force (GRF) data were collected via an instrumented treadmill (1000Hz; Bertec Corporation, Ohio, United States). Muscle-driven simulations of a representative gait cycle for the right limb were generated using OpenSim 3.3. A generic musculoskeletal model of the lower limb and trunk, with 21 degrees of freedom and 80 musculotendon actuators was used (Lai, Arnold, & Wakeling, 2017). Segment geometry and MTU properties were scaled based on a static calibration, with muscle strength scaled based on height and mass (Handsfield, Meyer, Hart, Abel, & Blemker, 2014). A traditional OpenSim pipeline (inverse kinematics and dynamics, residual reduction algorithm, computed muscle control [CMC]) was followed to estimate muscle excitations, forces, fibre lengths and velocities. These values were used as inputs into a muscle energetics model (Uchida, Hicks, Dembia, & Delp, 2016; Umberger, Gerritsen, & Martin, 2003). The model was used to calculate the whole-body metabolic power (W·kg⁻¹) across the gait cycle, as well as the individual contributions of muscles to the whole-body metabolic power.

Additional muscle-driven simulations were then generated with altered muscle parameters representing potential MTU adaptations (Folland & Williams, 2007) from strength training

(see Table 1). The MTU properties of individual muscles were altered together to simulate training targeting major muscle groups. Six muscle groups were examined, those being the hip extensors (superior, middle and inferior gluteus maximus; posterior gluteus medius and minimus; biceps femoris long head), hip adductors (adductor brevis, longus and magnus; gracilis), hip abductors (superior gluteus maximus; anterior, middle and posterior gluteus medius and minimus; piriformis; sartorius; tensor fascia latae), knee extensors (rectus femoris; vastus intermedius, lateralis and medialis), knee flexors (biceps femoris long and short heads; semimembranosus; semitendinosus), and plantarflexors (medial and lateral gastrocnemius; soleus). A total of seven alterations were made, resulting in 42 additional muscle-driven simulations (6 muscle groups x 7 MTU alterations) being performed on each running trial. Whole-body metabolic power and the metabolic power of muscles from these additional simulations were compared to the original simulation.

Table 1: Description of muscle tendon unit (MTU) parameters altered during simulations.

MTU Parameter	Description	Abbreviation
Maximum Isometric Force	20% increase in maximum isometric force with a corresponding increase in mass* (Uchida et al., 2016)	F _{Mass+}
Pennation Angle	10% increase in muscle fibre pennation angle	P _{Ang+}
Pennation Angle	10% decrease in muscle fibre pennation angle	P _{Ang-}
Tendon Stiffness	Reduced tendon strain to 4% at maximum isometric force (i.e. greater tendon stiffness)	T _{Stiff+}
Tendon Stiffness	Reduced tendon strain to 6% at maximum isometric force (i.e. reduced tendon stiffness)	T _{Stiff-}
Fibre Composition	10% increase in fast twitch fibre proportions [#]	F _{Twitch+}
Fibre Composition	10% decrease in fast twitch fibre proportions [#]	F _{Twitch-}

* - increase in mass was accounted for in both the muscle energetics model and by increasing the mass of relevant model segment/s (resulting in changes to ground reaction forces during running)

- changes in muscle fibre type composition were accounted for in the muscle energetics model

RESULTS AND DISCUSSION: Whole-body metabolic power from the baseline simulations was $26.47 \text{ W}\cdot\text{kg}^{-1}$ and $38.80 \text{ W}\cdot\text{kg}^{-1}$ for running at $4.5 \text{ m}\cdot\text{s}^{-1}$ and $6.5 \text{ m}\cdot\text{s}^{-1}$, respectively. Percentage changes for whole-body metabolic power with alterations to MTU parameters are presented in Figure 1. Altered muscle strength with a corresponding increase in mass (F_{Mass+}) had the largest effect in improving RE at both running speeds across nearly all muscle groups. Reductions in metabolic power were observed despite seeing slight increases in total energy consumed. Greater muscle forces were required to accelerate segments and counter increased ground reaction forces with added mass, resulting in slightly higher energy being consumed by muscles at certain points across the gait cycle. Given RE was normalised to body mass (i.e. $\text{W}\cdot\text{kg}^{-1}$), whole-body metabolic power was still found to decrease. These results suggest that the increases in strength resulted in the muscles becoming more efficient relative to their mass. Williams and Cavanagh (1987) identified an inverse relationship between maximal thigh circumference and submaximal VO_2 , suggesting caution might be necessary when considering the effect of adding muscle mass (particularly around the legs) on RE. However, the capacity to exert higher forces with greater efficiency may be a valid reason to use hypertrophy-specific training in distance runners. Slightly differing effects of F_{Mass+} were seen across the muscle groups when running speed was increased. Notably, a greater improvement in RE was seen with increases in hip extensor muscle strength relative to the other muscle groups at the higher speed. A greater focus on specific muscle groups depending on the event speed of the runner (e.g. 800m vs. 10,000m runner) may therefore be an important consideration for improving RE with strength training. Refinements to modelling procedures could be used to further understand the impact of added muscle mass on RE. Within the present study, mass was added globally to body segments relative to the position of muscles. This fails to acknowledge the potential changes in segment inertial properties where mass is added more locally (e.g. at the muscle belly). Further, the Hill-type MTU used did not account for mass in their contractile dynamics.

Muscle activation and contractile velocity is impacted by muscle mass and tissue inertia (Ross & Wakeling, 2016), and may therefore be an important consideration in muscle energetics.

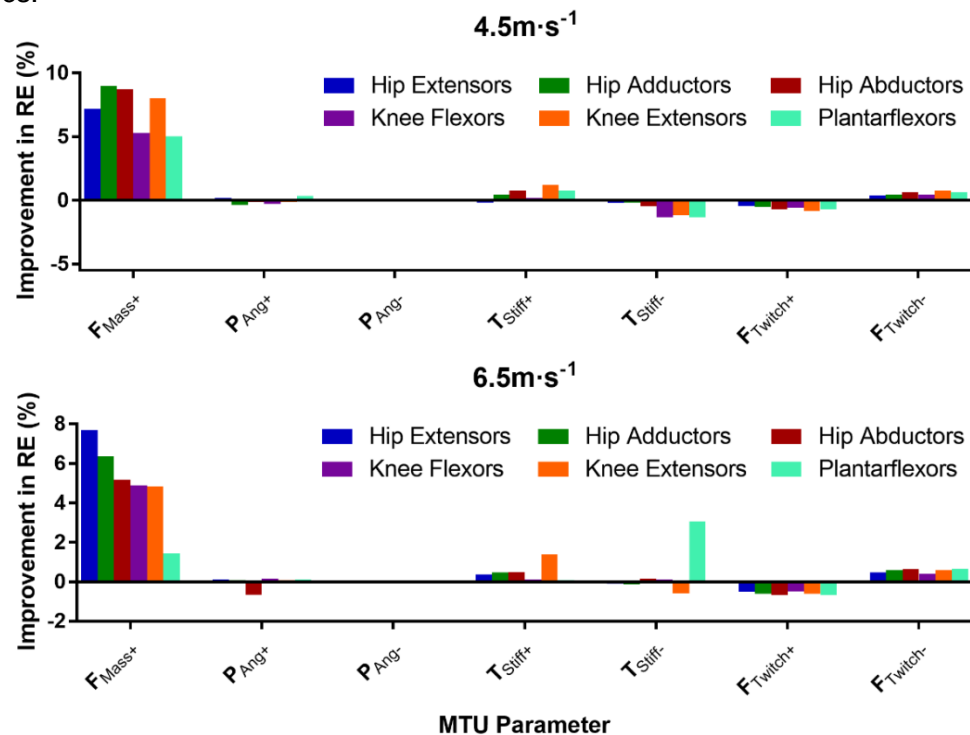


Figure 1: Percentage change in whole-body metabolic power relative to baseline simulation with altered muscle-tendon unit (MTU) parameters when running at 4.5 m·s⁻¹ and 6.5 m·s⁻¹.

Changes to tendon stiffness across muscle groups had a relatively consistent effect on RE. Stiffer (T_{Stiff+}) versus more compliant (T_{Stiff-}) tendons tended to result in improvements versus decrements in RE, respectively. Stiffer tendons possess a more forceful recoil, which can assist in the transmission of muscle forces to joint movement. This enhanced transmission may be the reason why certain improvements in RE were observed with T_{Stiff+} . An exception to this was at the higher running speed, more compliant plantarflexor tendons (T_{Stiff-}) resulted in improvements in RE at 6.5 m·s⁻¹, contrasting to the result at the lower speed. A reason for this may be that the more compliant tendon allowed the plantarflexor muscles to work closer to the optimal fibre length during running at 6.5 m·s⁻¹. In contrast, the compliant tendon shifted the plantarflexor muscles away (i.e. shorter) from their optimal fibre length at 4.5 m·s⁻¹. Optimal stiffness is tendon-, task- and speed-dependent (Ferris, Louie, & Farley, 1998), and thus the inconsistent changes are not unexpected. These results further highlight the need to consider both the speed of the running event and the muscle groups when designing strength training in distance runners.

Changes in muscle fibre composition across muscle groups had a consistent effect on RE. An increased ($F_{Twitch+}$) versus decreased ($F_{Twitch-}$) percentage of fast twitch fibres resulted in decrements and improvements in RE, respectively. These results, however, should be interpreted with caution. The change in fibre composition was only factored into the muscle energetics model, in which fast twitch fibres consume more energy (Uchida et al., 2016). Given that the change in fibre type was not incorporated within the CMC optimisation, no changes were observed in outputs entering the energetics model. Subsequently, the changes in RE were a simple response to the higher energy cost of having more fast twitch fibres, rather than any underlying neural or mechanical adaptations. In addition, the energetics model only incorporated two muscle fibre types – slow (i.e. type I) and fast (type II) twitch, without sub-categorising fast twitch fibres (i.e. IIa, IIb, IIx). Strength training changes the proportion of these fast twitch sub-categories (Folland & Williams, 2007), and

hence the inclusion of these within the optimisation and energetics model may reveal further details about such changes on RE. Unfortunately this was not possible within the energetics model used in this study. Development of muscle energetics models to include the varying fast twitch sub-categories is required for further investigation.

It is important to note that only one MTU parameter of separate muscle groups was altered in each simulation. This allowed a more specific interpretation of the alterations effect on RE, however may not represent a realistic response to training. Strength training programs generally target multiple muscle groups and induce numerous adaptations. Searching for the optimal combination of MTU adaptations across multiple muscle groups that maximises improvements in RE can therefore extend the work of this study. Investigation of additional MTU adaptations stemming from strength training, such as an altered force-velocity profile, can also be beneficial. It must be acknowledged that the energetics model used provides an estimate only, and may not provide as accurate results for RE as direct experimental measures (e.g. calorimetry). This study also used a single-subject design. Further examination of additional subjects with differing running biomechanics will allow for further understanding of how the various MTU adaptations alter RE.

CONCLUSION: This study highlights how targeting specific MTU adaptations within muscle groups may positively or negatively impact RE. Running speed and the muscle group appeared to have a modulating effect on how certain MTU parameters impacted RE. An individual's running speed in their chosen event may be an important consideration in the design of strength training. Targeting specific muscle groups and MTU adaptations, while considering the event speed of the runner may therefore be necessary when designing strength training programs for distance runners.

REFERENCES

- Bassett Jr, D.R. & Howley, E.T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Medicine and Science in Sports*, 32, 70-84.
- Denadai, B.S., de Aguiar, R.A., de Lima, L.C.R., Greco, C.C., & Caputo, F. (2017). Explosive training and heavy weight training are effective for improving running economy in endurance athletes: A systematic review and meta-analysis. *Sports Medicine*, 47, 545-554.
- Ferris, D.P., Louie, M., & Farley, C.T. (1998). Running in the real world: adjusting leg stiffness for different surfaces. *Proceedings of the Royal Society of London B: Biological Sciences*, 265, 989-994.
- Folland, J.P. & Williams, A.G. (2007). The adaptations to strength training: morphological and neurological contributions to increased strength. *Sports Medicine*, 37, 145-168.
- Handsfield, G.G., Meyer, C.H., Hart, J.M., Abel, M.F., & Blemker, S.S. (2014). Relationships of 35 lower limb muscles to height and body mass quantified using MRI. *Journal of Biomechanics*, 47, 631-638.
- Lai, A.K.M., Arnold, A.S., & Wakeling, J.M. (2017). Why are antagonist muscles co-activated in my simulation? A musculoskeletal model for analysing human locomotor tasks. *Annals of Biomedical Engineering*, 45, 2762-2774.
- McLean, S.G., Su, A., & van den Bogert, A.J. (2003). Development and validation of a 3-D model to predict knee joint loading during dynamic movement. *Journal of Biomechanical Engineering*, 125, 864-874.
- Paavolainen, L., Häkkinen, K., Hämmäläinen, I., Nummela, A., & Rusko, H. (1999). Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology*, 86, 1527-1533.
- Ross, S.A. & Wakeling, J.M. (2016). Muscle shortening velocity depends on tissue inertia and level of activation during submaximal contractions. *Biology Letters*, 12, 20151041.
- Uchida, T.K., Hicks, J.L., Dembia, C.L., & Delp, S.L. (2016). Stretching your energetic budget: How tendon compliance affects the metabolic cost of running. *PLoS One*, 11, e0150378.
- Umberger, B.R., Gerritsen, K.G.M., Martin, P.E. (2003). A model of human muscle energy expenditure. *Computer Methods in Biomechanics and Biomedical Engineering*, 6, 99-111.
- Williams, K.R. & Cavanagh, P.R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, 63, 1236-1245.