Review Article

IJMCL 2022; 4(2) 1–8

Contents lists available at Islamic World Science Citation Center (ISC)

International Journal of Motor Control and Learning (IJMCL)

Journal Homepage: http://www.ijmcl.com

Effect of Different Intervention on Running Economy - A Systematic Review of the Literature

Shahin Ketabi [a], *, Uwe Gustav Kersting [b]

[a] Physical Education and Sport Sciences, Department of Humanities, University of Kurdistan, Iran
[b] Institute of Biomechanics and Orthopedics, Collagen, Germany

ARTICLE INFO

Article history:
Received: 2022/01/08
Accepted: 2022/04/10
Available online: 2022/04/13

Keywords:

Running economy
Plyometric training
Strength training
Footwear
Energy return

ABSTRACT

Context: This article systematically reviews the available literature on biomechanically motivated interventions to improve running economy aside from conventional endurance training. It was aimed to identify the possible mechanisms behind the potential improvements and to extract principles to guide researchers and coaches in how to make use of this potential.

Evidence acquisition: The search strategy yielded 26 intervention papers and four reviews which were suitable for inclusion.

Results: It was concluded that plyometric and strength training protocols were consistently beneficial to reduce the oxygen consumption per distance traveled in steady state running showing an average effect size of 3.8%. Footwear interventions showed smaller effects of 1.9% on average but still may offer considerable improvements which can potentially be applied immediately.

Conclusions: It was suggested that the energy consumption savings achieved by footwear interventions are not realizable by energy return mechanisms of the footwear alone. It is most likely that footwear assists to improve RE by optimizing energy storage and return mechanisms within the biological system. Future research should aim at verifying this interplay to provide more efficient training programs as well as footwear which ameliorates the utilization of the mechanisms embedded within the human locomotor system.

1. Introduction

Running involves the conversion of muscular forces into forward directed motion of the body through complex cyclic movement patterns which incorporate nearly all the major muscles and joints. High performance running requires great skill and precise timing and it is common believe that it entails a graceful fluid motion in which all segmental movements have purpose and function to advance performance (Anderson, 1996). However, it is neither known which biomechanical descriptors constitute such a fluidly coordinated movement pattern, nor is there a generally applicable model which would allow for distinguishing between states or conditions of economic running. Running economy (RE) can simply be referred to as metabolic cost per distance covered at a given speed and metabolic cost during steady state running was shown to correlate well with running performance (Conley & Krahenbuhl, 1980; Costill et al., 1973). Running economy (RE) is a performance variable for distance runners. It can be affected by parameters such as equipment, running technique and surface. It has been shown that substantial mechanical energy will return by shoe integrated and that energy could be stored in the Muscle Tendon Units (MTU). While the association of running mechanics with metabolic processes and economy is not well understood and very complex, relating or linking the interconnections of mechanical and metabolic factors seems currently impossible. Such knowledge would allow for better predictions of improving economy and achieving better running performance ideally on an individual basis. It is obvious that for beginners any running training will first and foremost enhance metabolic and cardiovascular capacity while it seems that for athletes at higher performance levels other interventions may offer possibilities for further improvements. while a surface of intermediate compliance has been shown to offer potential for improved running economy (RE) through reduced foot contact time and increased step length (Anderson, 1996). The author pointed out that co-activation of the muscles around the knee and ankle joints increased the joint stiffness, which appears to be related to better RE (Anderson, 1996). It has also been indicated that the integration and timing of muscle activity to utilize the storage and release of elastic energy within the body system more effectively may lead to improvements in RE (Anderson, 1996; Saunders et al., 2004). However, increased co-contraction may require more metabolic substrates. It is therefore required to investigate to what extent increased muscle activity and potential benefits to muscle mechanics can be linked to improve RE. These training-induced improvements can be attributed to physiological rather than biomechanical modifications as no changes in biomechanical descriptors of running style that signaled changes in running economy were found (Lake & Cavanagh, 1996). It has repeatedly been shown that maximum oxygen uptake ($\dot{V}O_2max$) is not necessarily related to RE or, in other words, the highest $\dot{V}O_2max$ does not automatically imply best performance (Conley & Krahenbuhl, 1980; Costill et al., 1973). Therefore, it remains to be investigated which training or equipment related factors may allow for performance improvement apart from straight forward physiologic running training. The main purpose of this study was to a better understanding of interactions of biomechanical and physiological parameters is useful as this will enable coaches and athletes to improve performance.

---

* Corresponding author. **Shahin Ketabi,** *Department of humanities, University of Kurdistan, Iran.*
E-mail addresses: shahinketabi@gmail.com

1.1. *Rationale*

It was deducted by Williams and Cavanagh that 54% of the inter-individual variations in RE can be explained by kinematic variables (Bassett Jr et al., 1985; Williams & Cavanagh, 1987). Other authors have shown that the relationship observed between individual biomechanical factors and running economy is weak and it has been concluded that descriptive kinematic and kinetic parameters alone cannot explain the complexity of running economy (Burkett et al., 1985; Kyröläinen et al., 2001). Most studies focused on kinematics of the lower extremity and only very few studies have addressed upper body kinematics (Bassett Jr et al., 1985). Most biomechanical concepts occurred on lover limb and extremity; lower body is able to respond to varying impact load conditions to maintain Upper trunk stability. It was pointed out that co-activation of the muscles around the knee and ankle joints increases the joint stiffness, which appears to be related to better RE (Kyröläinen et al., 2001). Some authors believe that training which aims at improving performance and running economy could lead to changes in mechanical factors such as stride length and frequency, thus affecting muscle coordination and the storing and reuse of elastic energy within the body (Brooks et al., 1996). However, there is no conclusive evidence or theory on how this could be done or implemented into a training program. Therefore, a better understanding of interactions of biomechanical and physiological parameters is useful as this will enable coaches and athletes to improve performance.

1.2. *Terminology*

Running economy: RE is typically defined as the metabolic energy demand per distance covered at a given velocity of submaximal running, and is determined by measuring the steady-state consumption of oxygen ($\dot{V}O_2$) and the respiratory exchange ratio (Whipp & Wasserman, 1969). In other words, running is economical when the energy expenditure is small compared with the distance covered (Bergh et al., 1991; Bransford & Howley, 1977; Costill et al., 1973; Costill & Winrow, 1970; Mayhew, 1977). Running Economy is defined in equation (1).

Equation (1)

$$\boldsymbol{RE} = \frac{\boldsymbol{VO2\ (ml/min)}}{\boldsymbol{Body\,Weight\,(kg) * Velocity(Km/h)}}$$

Running Efficiency (REf): Studies have shown a weak relationship between efficiency and economy of running (Norman et al. 1976; Morgan et al. 1989). The term efficiency is probably the most abused and misunderstood term in human movement studies. Confusion and errors result from an improper definition of both the numerator and the denominator of the efficiency equation (Gaesser & Brooks, 1975; Whipp & Wasserman, 1969). There are two fundamental reasons for inefficiency: inefficiency in conversion of metabolic energy to mechanical energy and neurological inefficiency in the control of that energy. The metabolic energy depends on the condition of each muscle, the metabolic state (e.g., fatigue) of the muscle, the subject's diet, and any possible metabolic disorder.

1.3. *Objective*

The main objective of this paper was a systematic and specific review of the literature to focus on independent biomechanical interventions, other than pure endurance running training or endurance training varieties which seem not to have an influence on biomechanical parameters related to RE (Lake & Cavanagh, 1996). Based on an initial search on MEDLINE using the term 'running economy' the authors made an ad hoc decision to focus on two distinct types of intervention: footwear interventions and muscle-mechanics-directed training interventions. Interventions such as altitude training and nutritional changes were excluded. Given the large variety of non-endurance directed training programs it was decided to refer to muscle-mechanics-directed training as varieties ranging from static stretching over plyometric to pure strength training regimens which all aimed at explicitly or implicitly alter the properties of the muscle-tendon unit (MTU) of at least one major muscle group important for distance running.

2. Materials and Methods

Search strategy: Studies evaluating equipment, mainly footwear interventions, and 'biomechanical' training associated with running economy were considered for inclusion. It was required that the studies contained a paired comparison of the interventions used or a training and control group in the case of training studies. The following data bases were searched: MEDLINE (1966-present), CINAHL (1966-present), Embase (all years), PEDro, Google Scholar, and Cochrane library (Cochrane reviews, Cochrane central register of controlled trials). The following search terms were used: biomechanics; running economy; footwear; distance running; training; shod running, running mechanics; barefoot running; running efficiency; human biomechanics; musculoskeletal system; running surface; $\dot{V}O_2$. Reference lists of the included papers were also reviewed. Unpublished studies, case-series studies, non-peer reviewed publications, studies not involving humans, letters, opinion articles, non- English articles and abstracts were excluded.

2.1. *Review process*

All titles and abstracts found were downloaded into Reference Manager (version 12, Thomson Reuters). The data set was cross referenced and any duplicates were deleted, leaving a total of 1221 citations. If insufficient information was contained in the title and abstract to make a decision on a study, it was retained until the full text could be obtained for evaluation. There were 26 full papers which were included based on the selection criteria and these are listed in Tables 1 and 2. Four review papers were identified based on the search which were not included in the tables but served as a reference in the discussion (Barnes & Kilding, 2015; Fuller, Bellenger, et al., 2015; Shrier, 2004; Yamamoto et al., 2008). Further, several cross-sectional studies containing findings relevant to the discussion were included.

2.2. *Muscle-mechanics-directed training*

In accordance with our initial delimitation, the focus of this review is on training which directly or implicitly aims at altering the MTU's ability to store and release elastic energy by altering the stiffness of one or several muscle groups, or improves the interaction of muscle and tendon to dissipate less energy within the MTU. It is generally believed that increased strength allows the muscles to utilize more elastic energy storage and release and reduce the amount of energy wasted during eccentric contraction (Cavanagh, 1980; Saunders et al., 2004). It has been shown that such training clearly could improve running economy and with that also running performance. However, there are quite distinctive explanations on where and how more economical runners could store and recover more tendon elastic energy compared with uneconomical runners or, in other words, waste less muscle work (Di Prampero et al., 1986; Kyröläinen et al., 2001; Whipp & Wasserman, 1969; Williams & Cavanagh, 1987). The identified studies covering relevant interventions are listed in Table 1. Lake and Cavanagh (Lake & Cavanagh, 1996) used running training as an intervention which would refer to general endurance training but as the focus of the study was mainly on biomechanical parameters it fit the criteria for inclusion. Their results confirmed that simple progressive running training would not alter RE by leading to a more metabolically economic running technique for persons who were not trained at the start of the intervention period. Based on an intervention period of only six weeks, it could not be excluded that RE might change over extended training periods or maybe years of training. However, it supports the notion that RE may be difficult to change by running training alone.

Table 1. Biomechanical training & RE.

Author/s (date)	*Parameters?*	*Material and methods*	*Main finding*	*Comments*
Robert W. Spurrs, Aron J. Murphy 2003	Plyometric training	17 male runners, completed 6 weeks of plyometric training,	Improved RE led to changes in 3km running performance, as there were no corresponding alterations in V_O2max or lactate threshold.	Improve RE
Lake, Mark J. Cavanagh, Peter R. 1996	6-wk period of running training	Fifteen males were filmed and performed 10-min economy runs at 3.36 m•s-1 on a treadmill	The training-induced improvements in running performance could be attributed to physiological rather than biomechanical modifications. There were no changes in biomechanical descriptors of running style that signaled changes in running economy.	No significant change RE
Tamra L. Trehearn Robert J. Buresh 2009	Sit-and-reach flexibility	Eight collegiate distance runners (4 men and 4 women) served as subjects for this correlational study (age = 19.9 6 1.25 years; V_ o2max = 63.2 6 3.4 mlkg21min21).	Less flexible distance runners tended to be more economical, possibly as a result of the energy-efficient function of the elastic components in the muscles and tendons during the stretch-shortening cycle	Improve RE- not too much
Charles L. Dumke, Christopher M. Pfaffenroth 2010	muscle strength, power and muscle and tendon stiffness of the triceps-surae muscle group	Twelve well trained male runners (age = 21 ± 2.7 yr, height = 178.1 ± 7.1 cm, body mass =66.7 ± 3.2 kg, VO2max = 68.3±4.3 mL.kg–1.min–1,	Greater muscle stiffness and less power are associated with greater RE	Involved with better RE
Adamantios Arampatzis 2006	properties of muscle–tendon units (MTU)	Twenty-eight long-distance runners (Body mass: 76.8±6.7·kg, height: 182±6·cm, age: 28.1±4.5years), run on a treadmill at three velocities (3.0, 3.5 and 4.0·m·s–1) for 15 min each.	At low level forces the more compliant quadriceps tendon and aponeurosis will increase the force potential of the muscle while running and therefore the volume of active muscle at a given force generation will decrease.	Improve RE
Jacob M. Wilson, Lyndsey M. Hornbukle, 2010	Static stretching	Ten trained male distance runners aged 25 6 7 years with an average VO2max of 63.8 6 2.8 ml/kg/min were recruited.	Stretching before an endurance event may lower endurance performance and increase the energy cost of running.	Increase energy cost

Note: CG: control group, CMJ: counter-movement jump, DRJ: drop jump, EFF: efficiency, E_STRTR: explosive strength training, HW_STRTR, heavy weight strength training, MTS: muscle-tendon stiffness, MTU: muscle-tendon unit, MU: motor unit, OGR: over ground, PNF: proprioceptive neuromuscular facilitation, POW: power, RE: running economy, RFD: rate of force development, PLYTR: plyometric training, RUNTR: running training (endurance), RUN: running, SQJ: squat jump, STM: soft tissue mobilization. STR: strength, TR: training, TRD: treadmill, VO_{2max}: maximum oxygen consumption (a test or parameter, typically determined using a incremental running test on TRD, $VO_{2submax}$: submaximal oxygen uptake typically determined at a percent of VO_{2max} running velocity, IG: intervention group, Xover: cross-over design.

Table 2. Biomechanical Equipment & RE.

Author/s (date)	**Parameters?**	**Material and methods**	**Main finding**	**Comments**
B.M. Nigg, 2003	Shoes with different mechanical heel characteristics	Twenty male runners performed heel–toe running using two shoe conditions, one with a mainly elastic and a visco-elastic heel,	Changes in the heel material characteristics of running shoes were associated with (a) subject specific changes in oxygen consumption and (b) subject and muscle specific changes in the intensities of muscle activation before heel strike in the lower extremities	Improve RE
Sharon J. Dixon, Andrew C. Collop, 2000	Surface effects on ground reaction forces and lower extremity kinematics	Six heel-toe runners performed shod running trials over three surfaces: a conventional asphalt surface, a new rubber-modified asphalt surface, and an acrylic sports surface	It appears that the mechanism of adaptation varies among runners, highlighting the requirement of individual subject analyses.	Individually Improvement
Jean-Pierre R. Roy Darren J. Stefanyshen, 2005	Shoe Midsole Longitudinal Bending Stiffness	Carbon fiber plates were inserted into running shoe midsoles	Approximately a 1% metabolic energy savings was observed when subjects ran in a stiff midsole relative to the control midsole. Subjects with a greater body mass had a greater decrease in oxygen consumption rates in the stiff midsole relative to the control midsole condition. Increasing midsole longitudinal bending stiffness led to improvements in running economy	Improve RE
N. J. Hanson, K. Berg, P. Deka, J. R. Meendering, C. Ryan 2010	barefoot vs. running shod	10 healthy recreational runners, 5 male and 5 female, whose mean age was 23.8 ± 3.39 1) Barefoot on treadmill, 2) shod on treadmill, 3) barefoot over ground, and 4) shod over ground.	HR and RPE were significantly higher in the shod condition at 70 % of VO 2 max pace, barefoot running is more economical than running shod, both over ground and on a treadmill	Barefoot is more economical
Elizabeth C. Hardin, Antonie J. Vanden Bogert 2003	midsole hardness, surface stiffness, and running duration influence running kinematics	12 males ran at metabolic steady state under six conditions; combinations of midsole hardness and surface stiffness and 10 males ran for 30 min on a 12% downhill grade. In both experiments, subjects ran at 3.4 m·s1 on a treadmill.	Lower-extremity kinematics adapted to increased midsole hardness, surface stiffness, and running duration. Changes in limb posture at impact were interpreted as active adaptations that compensate for passive mechanical effects. The adaptations appeared to have the goal of minimizing metabolic cost at the expense of increased exposure to impact shock	Improve RE
Amy E. Kerdok, Andrew A. Biewener 2002	Surfaces of different stiffness's	Eight male subjects [mean body mass: 74.4 7.1 (SD) kg; leg length: 0.96 0.05 m] ran at 3.7 m/s over five different surface stiff nesses (75.4, 97.5, 216.8, 454.2, and 945.7 kN/m).	Surface stiffness affects running economy without affecting running support mechanics. We postulate that an increased energy rebound from the compliant surfaces studied contributes to the enhanced running economy	Affected RE
Catlin M, Dressendorfer R. 1979	Shoe weight	15 male distance runners, run with difference shoes,	Increased shoe weight will decrease running economy	Improve RE
Burkett LN, Kohrt WM, Buchbinder R. 1985	Effects of shoes	Twenty-one male runners who had been fitted with orthotics served as subjects. Subjects participated in three submaximal runs on a treadmill under the following conditions: barefoot, shoes, and shoes plus orthotics.	It appears that if orthotics does, in fact, improve running economy by improving running mechanics, the amount of improvement is negated by the additional cost of running associated with the mass of the orthotics.	Mechanics Improve RE
Frederick E, Clarke T, Larsen J, Cooper L.1983	shoe cushioning	10 well-trained male distance runners, weight (59.1 to 81.6), run 6 trials on treadmill, with difference shoes,	degree of cushioning of shoes has an influence on running economy, in this case well cushion shoes can reduce oxygen cost by as much as 2.8% over stiffer shoes of equal weight during running on treadmill	Improve RE
Jones BH, Knapik JJ, Daniels WL, Toner MM. 1986	shoes and boots	Seven subjects wore athletic shoes (mean weight = 514 ± 50g) and leather military boots (mean weight = 1371 ± 104g) at three walking speeds (4·0, 5·6 and 7·3km/hour) and two running speeds (8middot;9 and 10·5 km/hour).	These results are similar to those reported for men from other studies which found increments in energy cost of 0·7 to 0·9% per 100-g increase in weight of footwear.	Improve RE
Matthew F. Moran & Beau K. Greer 2012	Actuator Lugs	12 highly-trained male distance runners during four Submaximal running velocities.	The presence of external forefoot actuator lugs improved RE by ~1%, Although the mechanisms explaining this improvement are not clear.	Improve RE
Fuller JT, et al (2015)	5 km time-trial performance (5TT)	Seventy-six trained male runners must be aged 18–40years. running shoes (Asics Gel Cumulus-14, 15 or 16; mass 324 g/shoe; heel drop 9 mm) and participants allocated to the minimalist shoe condition will run in lightweight racing flats (Asics Piranha SP4; mass 125 g/shoe; heel drop 5 mm). Mass is reported for an average US size 9 (European size 42.5) shoe.	compare 5TT between shoe groups at the 6-week time point and injury incidence across the entire 26-week study period	reduce stride length1 and the amount of ankle dorsiflexion at initial ground contact,6 with the latter promoting a FF pattern.47
Wei, C., et al. (2020).	two differing warm-up protocols on running economy (RE)	All participants completed three different warm-up protocols (control, plyometric, and resistance warm-up) in a counterbalanced crossover design with trials separated by 48 h, using a Latin-square arrangement. Dependent variables measured in this study were RE at four running	RE, oxygen uptake; heart rate; respiratory exchange rate; expired ventilation; maximal perceived race readiness; rating of perceived exertion, time to exhaustion	The primary finding of this study was that the plyometric warm-up improved RE compared to the control warm-up

		velocities (7, 8, 9, and 10 km h–1), and leg stiffness.		
Warne, J. P., et al. (2015).	running economy (RE) and kinematics in conventional footwear	Twenty-three trained male runners, eight week combined minimalist footwear (MFW) and gait-retraining intervention	MFW and gait re-training intervention conventional running shoes	better RE in MFW was observed when compared to CRS due to shoe mass
Cheung, R. T., & Ngai, S. P. (2016).	running economy between	in this meta-analysis with a total of 168 runners, effect of running in barefoot, minimalists, and standard running shoes on RE	Barefoot running, standard running shoes	Barefoot running or running in minimalist may require lower utilization of oxygen than shod running
Fuller, J. T., (2015).	effect of footwear on running performance	1,044 records retrieved, 19 studies were included in the systematic review and 14 studies were included in the meta-analysis.	comfortable and stiff-soled shoes,	Certain models of footwear and footwear characteristics can improve running economy
Balsalobre-Fernández, C., Santos-Concejero, J., & Grivas, G. V. (2016).	running economy	systematic review with meta-analysis of controlled trials: 93 competitive, high-level middle- and long-distance runners	effect of strength training programs on RE	appropriate strategy to improve RE in highly trained middle- and long-distance runners.
Roschel, H., Barroso, R., (2015).	Running economy, VS, and lower-limb maximum dynamic strength (1 repetition maximum [1RM] half-squat)	Fifteen recreational runners were divided into RT or WBV + RT groups	resistance training (RT) and whole-body vibration training were assessed before and after the 6-week training period	There was a main time effect for 1RM, but no other statistically significant difference was observed.
Hung, K. C., et al. (2019).	core endurance and running economy	Twenty-one male college athletes	sport-specific endurance plank test (SEPT) and 4-stage treadmill incremental running test (TIRT).	week core training may improve static balance, core endurance, and running economy in college athletes.
Denadai, B. S., et al. (2017).	RE	endurance running athletes. analysis comprised 20 effects in 16 relevant studies published up to August 2015	concurrent training program, explosive, heavy weight	Explosive training and heavy weight training are effective concurrent training methods aiming to improve RE
Drum, S. N., Rappelt, L., & Donath, L. (2019).	RE, trunk muscle isometric rate of force production, and lactate response in runners.	Seven well-trained runners (2 males and 5 females) randomly underwent control (CON)	Individual anaerobic threshold, running treadmill until voluntary exhaustion	UPR and TRK conditions might adversely impact running economy at a high intensity, steady state running pace
Lussiana, T., et al (2019).	lower duty factor (DF), of leg swing, ground contact time, running step	Forty well-trained runners were divided in two groups based on their mean DF measured across a range of speeds.	centre of mass (COM) displacement and EC	DF_{low} exhibited more symmetrical patterns between braking and propulsion phases in terms of time and vertical COM displacement than DF_{high}. DF_{high} limited global vertical COM displacements in favour of horizontal progression during ground contact. Despite these running kinematics differences, no significant difference in EC was observed between groups
Tam, N., et al. (2019).	certain neuromuscular and spatiotemporal biomechanical factors associated with running economy	Thirty trained runners performed a 6-min constant-speed running set at 3.3 m·s−1, where oxygen consumption was assesse	assess kinematics, kinetics, and muscle activity. Spatiotemporal gait variables, joint stiffness, preactivation, and stance-phase muscle activity	More economical runners presented with short ground-contact times ($r = .639$, $P < .001$) and greater stride frequencies ($r = −.630$, $P < .001$). Lower ankle and greater knee stiffness were associated with lower oxygen consumption ($r = .527$, $P = .007$ and $r = .384$, $P = .043$, respectively). Only lateral gastrocnemius–tibialis anterior coactivation during stance was associated with lower oxygen cost of transport ($r = .672$, $P < .0001$)
Hunter, I., et al. (2019).	RE	Nineteen subjects performed two 5-minute trials at 4.44m/s wearing the Adidas Adios Boost (AB), Nike Zoom Streak (ZS), and Nike Vaporfly 4% (VP) in random order.	metabolically and mechanically compare the consumer version of the Nike Vaporfly 4% shoe to two other popular marathon shoes, and determine differences in running economy	These results indicate that use of the VP shoe results in improved running economy,

Three studies were identified which implemented plyometric training on top of normal running training over 6 – 9 weeks. The selection and volumes of plyometric exercises was different between studies but generally included bounds, hops and jumps with an eccentric-concentric movement cycle as the general characteristic of the training to utilize the stretch-shortening cycle as discussed in two reviews on the topic (Horita et al., 1996; Kyröläinen et al., 2001). Consistently, there was a significant improvement of RE ranging from 2 – 4.1% for at least one of the tested submaximal running speeds while V̇O_2max did not change. Generally, subjects improved their strength or jump performance while this did not apply for the study by Turner et al. (2003) (Turner et al., 2003). However, in their study RE was improved for all three submaximal running speeds. One study (Guglielmo et al., 2009) compared the effect of heavy-weight and explosive strength training over a period of 4 weeks. While both improved RE significantly, they found that heavy strength training had a greater effect. While these studies applied different selections of additional neuromechanical tests to explain these improvements a general conclusion might be that mechanical changes at the MTU are the likely causes for the improvements in RE.

One study was found applying acute stretching focusing on muscle groups crossing the hip (Godges et al., 1989) prior to repeated submaximal running tests. The considerable improvements of up to 4.2% in RE (6.6% for walking) after stretching were explained by an increased range of motion which dynamically may decrease the force required by antagonistic muscles followed by a reduced metabolic demand to maintain the running motion. While such a mechanism might be intuitive muscle contraction was not quantified in this study. This stands in contrast to a study by Wilson et al. (2010) which demonstrated that acute general stretching prior to submaximal running tests lead to a performance decrease of 3.4%. The suggested mechanism was a change in the muscle-tendon interaction which affects energy storage and release in the triceps surae (Wilson et al., 2010). Various stretching paradigms were used or comparted in these studies which are believed to alter muscle innervation or recruitment which may serve as another pathway for interpretation. However, as these parameters were not investigated such mechanism remain speculative and too general. In a review (Shrier, 2004), in which 23 papers on the effect of stretching on performance in general were included it was stated that regular static stretching may improve strength and jump performance but has no effect on running performance. However, RE was only directly assessed in one paper within this review.

The most detailed study on training effects on triceps surae properties and RE was presented by Albracht and Arampatzis (2013) who performed resistance training of the triceps surae over 14 weeks. The training led to a stiffening of the Achilles tendon and aponeurosis and a strength increase in the active component of the triceps surae. This combination was interpreted to allow for a better energy storage and subsequent release during the ground contact. This interpretation receives further support from several studies not focusing on running training alone. It was previously shown that the amount of energy stored in a tendon depends on the mechanical properties of the MTU such that tendon force inversely relates to the moment arm of the tendon for a given kinematic pattern and hence kinetic pattern. The importance of moment arm scaling and locomotion, elastic energetic storage and return has been pointed out by others (Burkett et al., 1985; Carrier et al., 1994). Jared and Brian (Fletcher et al., 2010) have demonstrated that both triceps surae tendon stiffness and RE can change acutely, and that both variables appear to change together.

It was suggested that a higher Achilles tendon stiffness is associated with a lower energy cost to run a given distance. This observation must be viewed in conjunction with previous suggestions that there seems to be an optimal tendon stiffness beyond which the energy cost of running must increase (Cavagna et al., 1964; Lichtwark & Wilson, 2008). From a mechanical point of view there are two possible ways to influence the energy storage and release mechanisms in the triceps surae MTU. If running technique is unchanged MTU stiffness may be the main factor but changes in running technique, i.e., a change in the centre of pressure can affect the moment arm of the GRF and with that the gear ratio (Albracht & Arampatzis, 2013; Braunstein et al., 2010).

Based on the papers identified in this review (Table 1) it appears that running technique is not changed after training, however, as RE measurements are typically performed on treadmills kinetic changes may not have been fully covered in these studies. Thus, the changes in the mechanical properties of the MTU appear to be the explaining factor which can be exploited by specific strength training. The fact that plyometric training consistently leads to improvements may only in parts be based on the potential motor control aspects but rather on the high forces produced during eccentric contractions leading to a stiffness increase in the MTU.

This conclusion is supported by a recent review paper (Yamamoto et al., 2008) which identified five longitudinal studies using highly trained runners, which all confirmed that any form of high intensity strength training which potentially affects the thickness and with that the stiffness of the Achilles tendon leads to improvements in RE. A second review by Barnes and Kilding (2014), which confirmed this observation for a number of strength training regimens while the authors pointed at the fact that neuromuscular components as well as metabolic changes induced by, e.g., altitude training have the capacity to change RE. Therefore, the multifactorial nature of running performance always needs to be taken into full account.

2.3. *Footwear*

From a mechanical point of view, it seems obvious that the interaction of the body with the surface may have considerable effects on running economy. A straight forward intervention is to alter shoe mass as the footwear would need to be lifted and accelerated during each step. Increased shoe weight will decrease running economy (Catlin & Dressendorfer, 1979; Stefanyshyn et al., 2000; Stefanyshyn, 2000). Several studies were identified, which have shown that cushioning has an influence on running economy, however, the results are not consistent. In one case, a well cushioned shoes reduced oxygen cost by as much as 2.8% over stiffer shoes of equal weight during running on a treadmill (Frederick, 1983; Frederick et al., 1983). The authors suggested that if the shoe provides inadequate shock absorption the runner produces great muscular effort to compensate for this lack of cushioning. Hamill et al. (1988) compared race flats to standard shoes and confirmed the weight effects from previous studies (Hamill et al., 1988). The focus of this study was to assess rearfoot movement which was significantly different between shoes and did not change substantially over time and was therefore considered a shoe design effect. Thomson et al. (1999) provided a finite element model of the midsole-foot interaction and predicted the effect of material related energy return to have an effect on RE (Thomson et al., 1999). They then compared two quite distinct midsole materials but could not demonstrate any measureable effect on RE experimentally on a group of 14 runners. One distinctly different intervention was proposed by Mercer et al. (2003), who found similar energy consumption in a 1.7 kg heavier spring-boot and a standard running shoe, however, this type of footwear appears impractical and would not be allowed to be used in competitions (Mercer et al., 2003). Wei, C., (2020) founded that Moreover, elastic energy induced by a plyometric warm-up can be stored in the tendons and skeletal muscles, making an extensive contribution to propulsion. This may reduce ground contact times, and is likely to further reduce energy consumption (improve the RE) during endurance exercise. The above mechanisms may explain the improved RE following the plyometric warm-up protocol (Wei et al., 2020).More recently, Hardin et al. (2004) explored combinations of surface stiffness, midsole hardness and prolonged downhill running on sagittal plane kinematics, EMG and RE. While the surface hardness changed knee and hip kinematics as well as RE substantially there was only a comparably small effect of midsole hardness. Only for the hard surface condition a significantly higher ankle angular velocity was observed, which related to a higher oxygen consumption (Hardin et al., 2004). Nigg et al. (2003) compared a more viscous to a more elastic midsole for a sample of 20 runners. They found highly individual responses with some subjects showing a increase in VO2submax for the ‘elastic’ sole while others showed similar improvements for the ‘viscous’ shoe. The authors explained this effect by individual adjustments in muscle pre-activation to regulate the level of impact force (Nigg et al., 2003). These muscle activations would then explain the alterations in oxygen consumption. From the same group it was suggested that individual perceptions of comfort may be an indicator for this effect of muscular effort on RE, which is supported by a paper of Luo et al. (2009) who let runners select the most and least comfortable shoe from a set of five different models. They confirmed a significant RE effect when comparing these two shoes while most but not all subjects selected the respective same models indicating that individual preferences do play a role (Luo et al., 2009).

Most of the early studies on running footwear have aimed at changes in midsole hardness or cushioning based on the assumption that high impact forces might relate to running injuries and therefore maximum cushioning would be desirable. While this notion has been questioned within the last decade (Nigg, 2001), Roy and Stefanyshyn (2006) assessed the effect of a change in midsole bending stiffness to improve running economy and found that an optimum bending stiffness may exist at which energy consumption is minimal (Roy & Stefanyshyn, 2006).

Rubin et al. (2009) could not ascertain any effects on RE when comparing a motion control shoe to a standard running shoe, while Kersting et al. (2015; submitted) have shown a similar result for medial and lateral inserts in that some subjects may benefit from lateral inserts by a potential energy return effect in the medial structures around the ankle joint (Stacoff et al. 1989) or the foot arch (Ker et al., 1987) while others respond with an increase muscle activation which then leads to a higher oxygen demand. Finally, Moran and Greer (2013) and Worobets et al (2014) could show midsole characteristics other than overall material hardness may improve RE by enabling an energy return like effect which was reasonably consistent across groups of trained runners in their studies (Moran & Greer, 2013; Worobets et al., 2014). As highlighted by Worobets et al. (2014) it has to be noted that very different shoe interventions have been used in various studies which make a comparison or general conclusion difficult. Based on their results a continuous, softer but more elastic midsole is advantageous which was not consistent with other studies varying hardness und the heel alone (Frederick et al., 1986; Nigg et al., 2003).

In recent years, a commercial trend to provide footwear which enables a more ‘natural’ running style has been observed. With reference to anthropological observations natural running was hypothesized to be more efficient and less injury prone (Lieberman et al., 2010). It is beyond the scope of this paper to address effects of running in MS on injury risk. However, it has been indicated in a review that no study has yet been provided to support this notion. Comparisons of RE effects of just barefoot running to running in standard running shoes (Hanson et al., 2011) are not included in this review but some studies within this group of papers include comparisons of minimal shoes (MS) to conventional running shoes (Lussiana et al., 2013; Moore et al., 2014; Perl et al., 2012; Squadrone & Gallozzi, 2009). Across these studies, inconsistent results are reported as shoe weight, habituation, stride length and rate (SR) and footfall pattern seem to show multiple interactions which are not fully addressed in the study designs used. A key paper in this area may be Perl et al. (2012), who tested runners who were accustomed to minimal shoe or barefoot running. While there was only a slightly better economy when running with minimal shoes a substantial interaction with foot strike pattern was demonstrated on an individual level. In Perl et al. (2012) and several of the studies named above (Moran & Greer, 2013; Nigg et al., 2003; Worobets et al., 2014) the high individuality of RE alterations to systematic footwear variations was highlighted. While group effects were very small or non-existent all authors showed individual responses being in an order of up to 10%. Some of these studies did not include any material related energy return effect, while it was estimated by Stefanyshyn and Nigg (2000) that energy return from midsole material could theoretically be maximal 2% but only if the material was ideally elastic which, in reality, is not the case. It is therefore questionably if any of the reported energy savings are a direct result from mechanical properties of the shoes (Stefanyshyn et al., 2000).

3. Discussion and Conclusion

In this review, 26 papers were identified which investigated 'non-endurance' training programs or footwear interventions to improve running economy in experienced runners. Training interventions show consistently positive effects if the intervention entails a strength component with eccentric and heavy strength training regimens being most efficient while stretching, in most cases, does not acutely improve RE or may even be counterproductive. The average effects of interventions showing a reduced oxygen consumption were in an order of 2 – 6% (average 3.8%, Table 1). Footwear studies, in this case averaging the effect size of non-weight related interventions, allow for average changes of 0 – 4.8% (average 1.9%, Table 2). If effects on individuals were reported these differences of up to approximately 10% were reported which must be considered substantial in regard to long distance running performance. Therefore, the main result of this review is that both intervention strategies may lead to meaningful reductions in oxygen consumption which would have substantial effects on performance.

For both types of studies reviewed, quite variable experimental designs and, more importantly, quite variable interventions have been used. It is therefore very difficult to derive specific mechanisms leading to the respective changes. In regard to the training studies, it seems apparent that any type of strength training may induce both mechanical and neurological adaptations in a trained muscle group. Factors such as motoneuron activity, muscle fibre recruitment or timing of recruitment are inherently problematic to assess in repeated measures designs and can therefore only be indirectly discussed. The fact that explosive strength training, in this case concentric training (Guglielmo et al., 2009), appears less effective may indicate the recruitment being of minor importance. I may therefore be argued that the high eccentric forces generated during plyometric training (Saunders et al., 2004; Spurrs et al., 2003; Turner et al., 2003) or submaximal and maximal strength training (Albracht & Arampatzis, 2013; Guglielmo et al., 2009) are providing the most effective stimulus. This interpretation is well documented in the study by Albracht and Arampatzis (2013) which identifies the stiffness, in this case the thickness, of the tendon in combination with greater muscular strength as a prerequisite for improving energy storage and release. The mechanism may then be that muscle fibres can generate higher forces at slow or negative contraction velocities as it was demonstrated for submaximal running (Ishikawa et al., 2007; Lichtwark & Wilson, 2008) which can then increase the energy stored in the stiffened Achilles tendon.

In regard to footwear interventions, it may become even more difficult to extract a general mechanism. It appears that midsole hardness or elasticity is a factor which has been repeatedly investigated, however, with inconsistent results indicating that it may not be the elasticity of the material itself which allows for energy storage and release alone. It was pointed out by Shorten (1993) as well as by Stefanyshyn and Nigg (2000) that energy return as it is often suggested in advertisements of various shoe manufacturers is very difficult to implement in footwear. Some of the studies included in the current review demonstrate that energy return effects seem possible but in none of the studies this effect was consistent across athletes which directed the focus in the discussion sections of these papers to the individuality within the observed responses. As indicated by Stefanyshyn, an ideal elastic shoe could only return about 2% of the energy required per one step of steady state running (500 J). In reality, viscoelastic materials may only return 20% of energy which would reduce this theoretical limit to 0.4% (Stefanyshyn et al., 2000), however, Worobets et al. (2004) used a midsole material returning 32% of the deformation work, improving this ratio slightly. Referring to the bending tests used in Roy and Stefanyshyn (2005) the work for bending the stiffest shoe was 0.285 J resulting in less than 0.1% energy stored within the shoe per step, which would potentially return even less energy due to hysteresis. It is therefore obvious that the partially significant effects cannot be a direct effect of the material properties of the footwear (Roy & Stefanyshyn, 2006).

It is therefore suggested that a possible interpretation is anchored in the study by Perl et al. (2012) who systematically varied footwear and footstrike pattern which led to individual changes in RE of up to 10%. Their suggestion, that energy might be stored in the deformation of the arch and/or the triceps surae MTU may need to be joined with the observations from the training studies reviewed here. Based on these concepts it appears conceivable that muscle activity, pre-activation (Nigg et al., 2003) as well as dynamic contractions, leading to small adjustments in kinematics and/or joint stiffness are made to facilitate energy storage and return in the best possible manner including several/all elastic structures within the leg-foot system. An additional lengthening of the triceps surae by 5 mm might be plausible by changes in shoe geometry such as heel spring, midsole deformation, inserts or foot strike pattern. Based on the data provided by Albracht and Arampatzis (2013) this would store 22.5 J within the tendon at the maximum force of 4500 N, equating to 4.5% per step, increasing tendon strain by about 30%. Given a hysteresis of the Achilles tendon measured at 5+/-2% (Peltonen et al., 2013) a much greater effect as for shoe materials might be obtained. As training studies reviewed here demonstrated 4% average effect size it is suggested that any footwear intervention showing measurable and relevant RE improvements have to make indirect use of the energy storage and return capacity of the human locomotor system. The question how such interaction could be facilitated and practically used was not addressed in the papers reviewed.

With reference to a study by Braunstein et al. (2010), footwear offers the possibility to alter the gear ratio at the ankle and knee joint in certain phases of the ground contact (Braunstein et al., 2010). It is thus possible that midsole hardness and geometry, as well as a combination thereof, may provide subtle changes in muscle force generation over time which in certain instances, i.e., in some individuals, may lead to a better economy. As most studies reviewed in this paper have not identified ground reaction force parameters or joint moments the time course of the gear ratio cannot be extracted. However, this interpretation potentially allows for an explanation of the inconsistent findings from footwear intervention studies. It is therefore recommended to investigate footwear effects in the future including gear ratios or/and the effect on MTU loading.

Various forms of strength training have been shown to improve RE without increasing metabolic capacity which might be difficult for elite athletes who already train at the limit of their endurance trainability. It seems that these effects can be best explained by changes in the triceps surae MTU mechanical properties as a stiffer tendon in conjunction with stronger muscles can enhance energy storage and release mechanisms during ground contact. Thus a heavy load strength training regimen aiming at stiffening of the tendon may be advantageous. It needs, however, been taken into account that a more compliant patella tendon may also be advantageous (Karamanidis & Arampatzis, 2005). While weight reductions of running shoes consistently show advances in RE it cannot be concluded if minimalist shoes advance performance. Various footwear interventions appear to potentially improve RE while some more recent footwear developments seem to show consistent effects. As some individuals may benefit more than others from shoe modifications it was suggested that body-inherent energy return mechanisms may be facilitated. If this is the case a comprehensive individual assessment of footwear effects including internal energy exchange mechanisms may be the only way to better understand the mechanisms used.

Practical Implications

This review shows that both heavy load calf strength training programs as well as footwear modifications can improve submaximal running performance by several percent. Such improvements would be substantial in regard to performance on the ambitious to elite level for middle- and long-distance runners. We recommend that strength training of the triceps surae muscle groups should be included into the training of high-level distance runners. Footwear seems to offer a more direct and simple way of improving performance with the limitation that these beneficial effects may not apply to all athletes.

Conflict of interest

The authors have no conflicts of interest to declare which might have influenced the preparation of this manuscript.

References

Albracht, K., & Arampatzis, A. (2013). Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. *European journal of applied physiology*, *113*(6), 1605-1615.

Anderson, T. (1996). Biomechanics and running economy. *Sports medicine*, *22*(2), 76-89.

Balsalobre-Fernández, C., Santos-Concejero, J., & Grivas, G. V. (2016). Effects of strength training on running economy in highly trained runners: a systematic review with meta-analysis of controlled trials. *Journal of strength and conditioning research*, *30*(8), 2361-2368.

Barnes, K. R., & Kilding, A. E. (2015). Strategies to improve running economy. *Sports medicine*, *45*(1), 37-56.

Bassett Jr, D. R., Giese, M. D., Nagle, F. J., Ward, A., Raab, D. M., & Balke, B. (1985). Aerobic requirements of overground versus treadmill running. *Medicine and Science in Sports and Exercise*, *17*(4), 477-481.

Bergh, U., Sjödin, B., Forsberg, A., & Svedenhag, J. (1991). The relationship between body mass and oxygen uptake during running in humans. *Medicine and Science in Sports and Exercise*, *23*(2), 205-211.

Bransford, D. R., & Howley, E. T. (1977). Oxygen cost of running in trained and untrained men and women. *Medicine and science in sports*, *9*(1), 41-44.

Braunstein, B., Arampatzis, A., Eysel, P., & Brüggemann, G.-P. (2010). Footwear affects the gearing at the ankle and knee joints during running. *Journal of Biomechanics*, *43*(11), 2120-2125.

Brooks, G. A., Fahey, T. D., & White, T. P. (1996). *Exercise physiology: human bioenergetics and its applications*. Mayfield publishing company.

Burkett, L., Kohrt, W. M., & Buchbinder, R. (1985). Effects of shoes and foot orthotics on VO2 and selected frontal plane knee kinematics. *Medicine and Science in Sports and Exercise*, *17*(1), 158-163.

Carrier, D. R., Heglund, N. C., & Earls, K. D. (1994). Variable gearing during locomotion in the human musculoskeletal system. *Science*, *265*(5172), 651-653.

Catlin, M., & Dressendorfer, R. (1979). Effect of shoe weight on the energy-cost of running. Medicine and Science in Sports and Exercise,

Cavagna, G. A., Saibene, F. P., & Margaria, R. (1964). Mechanical work in running. *Journal of applied physiology*, *19*(2), 249-256.

Cavanagh, P. (1980). The Running Shoe Book (Anderson World, CA: Mountain View).

Cheung, R., & Ngai, S. P. (2016). Effects of footwear on running economy in distance runners: A meta-analytical review. *Journal of science and medicine in sport*, *19*(3), 260-266.

Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. *Med Sci Sports Exerc*, *12*(5), 357-360.

Costill, D., THOMASON, H., & ROBERTS, E. (1973). Fractional utilization of the aerobic capacity during distance running. *Medicine and science in sports*, *5*(4), 248-252.

Costill, D. L., & Winrow, E. (1970). A comparison of two middle-aged ultramarathon runners. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *41*(2), 135-139.

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*(3), 545-554.

Di Prampero, P., Atchou, G., Brückner, J.-C., & Moia, C. (1986). The energetics of endurance running. *European Journal of Applied Physiology and Occupational Physiology*, *55*(3), 259-266.

Drum, S. N., Rappelt, L., & Donath, L. (2019). Trunk and Upper Body Fatigue Adversely Affect Running Economy: A Three-Armed Randomized Controlled Crossover Pilot Trial. *Sports*, *7*(8), 195.

Fletcher, J. R., Esau, S. P., & MacIntosh, B. R. (2010). Changes in tendon stiffness and running economy in highly trained distance runners. *European journal of applied physiology*, *110*(5), 1037-1046.

Frederick, E. (1983). Measuring the effects of shoes and surfaces on the economy of locomotion. *Biomechanical Aspects of Sport Shoes and Playing Surfaces*, *93*.

Frederick, E., Clarke, T., Larsen, J., & Cooper, L. (1983). The effects of shoe cushioning on the oxygen demands of running. *Biomechanical Measurement of Running Shoe Cushioning Properties. Biomechanical Aspects of Sport Shoes and Playing Surfaces. University of Calgary, Calgary, AB*, 107-114.

Frederick, E., Howley, E., & Powers, S. (1986). Lower oxygen demands of running in soft-soled shoes. *Research Quarterly for Exercise and Sport*, *57*(2), 174-177.

Fuller, J. T., Bellenger, C. R., Thewlis, D., Tsiros, M. D., & Buckley, J. D. (2015). The effect of footwear on running performance and running economy in distance runners. *Sports medicine*, *45*(3), 411-422.

Fuller, J. T., Thewlis, D., Tsiros, M. D., Brown, N. A., & Buckley, J. D. (2015). The long-term effect of minimalist shoes on running performance and injury: design of a randomised controlled trial. *BMJ open*, *5*(8), e008307.

Gaesser, G. A., & Brooks, G. A. (1975). Muscular efficiency during steady-rate exercise: effects of speed and work rate. *Journal of applied physiology*, *38*(6), 1132-1139.

Godges, J. J., MacRae, H., Longdon, C., Tinberg, C., & MacRae, P. (1989). The effects of two stretching procedures on hip range of motion and gait economy. *Journal of Orthopaedic & Sports Physical Therapy*, *10*(9), 350-357.

Guglielmo, L., Greco, C., & Denadai, B. (2009). Effects of strength training on running economy. *International Journal of Sports Medicine*, *30*(01), 27-32.

Hamill, J., Freedson, P. S., Boda, W., & Reichsman, F. (1988). Effects of shoe type on cardiorespiratory responses and rearfoot motion during treadmill running. *Medicine and Science in Sports and Exercise*, *20*(5), 515-521.

Hanson, N., Berg, K., Deka, P., Meendering, J., & Ryan, C. (2011). Oxygen cost of running barefoot vs. running shod. *International Journal of Sports Medicine*, *32*(06), 401-406.

Hardin, E. C., Van Den Bogert, A. J., & Hamill, J. (2004). Kinematic adaptations during running: effects of footwear, surface, and duration. *Medicine & Science in Sports & Exercise*, *36*(5), 838-844.

Horita, T., Komi, P., Nicol, C., & Kyröläinen, H. (1996). Stretch shortening cycle fatigue: interactions among joint stiness, reflex, and muscle mechanical performance in the drop jump. *European Journal of Applied Physiology and Occupational Physiology*, *73*(5), 393-403.

Hung, K.-C., Chung, H.-W., Yu, C. C.-W., Lai, H.-C., & Sun, F.-H. (2019). Effects of 8-week core training on core endurance and running economy. *PloS one*, *14*(3), e0213158.

Hunter, I., McLeod, A., Valentine, D., Low, T., Ward, J., & Hager, R. (2019). Running economy, mechanics, and marathon racing shoes. *Journal of sports sciences*, *37*(20), 2367-2373.

Ishikawa, M., Pakaslahti, J., & Komi, P. (2007). Medial gastrocnemius muscle behavior during human running and walking. *Gait & posture*, *25*(3), 380-384.

Karamanidis, K., & Arampatzis, A. (2005). Mechanical and morphological properties of different muscle–tendon units in the lower extremity and running mechanics: effect of aging and physical activity. *Journal of Experimental Biology*, *208*(20), 3907-3923.

Kyröläinen, H., Belli, A., & Komi, P. V. (2001). Biomechanical factors affecting running economy. *Medicine & Science in Sports & Exercise*, *33*(8), 1330-1337.

Lake, M. J., & Cavanagh, P. R. (1996). Six weeks of training does not change running mechanics or improve running economy. *Medicine and Science in Sports and Exercise*, *28*(7), 860-869.

Lichtwark, G., & Wilson, A. (2008). Optimal muscle fascicle length and tendon stiffness for maximising gastrocnemius efficiency during human walking and running. *Journal of theoretical biology*, *252*(4), 662-673.

Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'andrea, S., Davis, I. S., Mang'Eni, R. O., & Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*(7280), 531-535.

Luo, G., Stergiou, P., Worobets, J., Nigg, B., & Stefanyshyn, D. (2009). Improved footwear comfort reduces oxygen consumption during running. *Footwear Science*, *1*(1), 25-29.

Lussiana, T., Fabre, N., Hébert-Losier, K., & Mourot, L. (2013). Effect of slope and footwear on running economy and kinematics. *Scandinavian Journal of Medicine & Science in Sports*, *23*(4), e246-e253.

Lussiana, T., Patoz, A., Gindre, C., Mourot, L., & Hébert-Losier, K. (2019). The implications of time on the ground on running economy: less is not always better. *Journal of Experimental Biology*, *222*(6), jeb192047.

Mayhew, J. (1977). Oxygen cost and energy expenditure of running in trained runners. *British journal of sports medicine*, *11*(3), 116-121.

Mercer, J. A., Branks, D. A., Wasserman, S. K., & Ross, C. M. (2003). Physiological cost of running while wearing spring-boots. *Journal of strength and conditioning research*, *17*(2), 314-318.

Moore, I. S., Jones, A., & Dixon, S. (2014). The pursuit of improved running performance: can changes in cushioning and somatosensory feedback influence running economy and injury risk? *Footwear Science*, *6*(1), 1-11.

Moran, M. F., & Greer, B. K. (2013). Influence of midsole 'actuator lugs' on running economy in trained distance runners. *Footwear Science*, *5*(2), 91-99.

Nigg, B. M. (2001). The role of impact forces and foot pronation: a new paradigm. *Clinical journal of sport medicine*, *11*(1), 2-9.

Nigg, B. M., Stefanyshyn, D., Cole, G., Stergiou, P., & Miller, J. (2003). The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. *Journal of Biomechanics*, *36*(4), 569-575.

Peltonen, J., Cronin, N. J., Stenroth, L., Finni, T., & Avela, J. (2013). Viscoelastic properties of the Achilles tendon in vivo. *Springerplus*, *2*(1), 1-8.

Perl, D. P., Daoud, A. I., & Lieberman, D. E. (2012). Effects of footwear and strike type on running economy. *Med Sci Sports Exerc*, *44*(7), 1335-1343.

Roschel, H., Barroso, R., Tricoli, V., Batista, M. A., Acquesta, F. M., Serrão, J. C., & Ugrinowitsch, C. (2015). Effects of strength training associated with whole-body vibration training on running economy and vertical stiffness. *The Journal of Strength & Conditioning Research*, *29*(8), 2215-2220.

Roy, J.-P. R., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine & Science in Sports & Exercise*, *38*(3), 562-569.

Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports medicine*, *34*(7), 465-485.

Shrier, I. (2004). Does stretching improve performance? a systematic and critical review of the literature. *Clinical journal of sport medicine*, *14*(5), 267-273.

Spurrs, R. W., Murphy, A. J., & Watsford, M. L. (2003). The effect of plyometric training on distance running performance. *European journal of applied physiology*, *89*(1), 1-7.

Squadrone, R., & Gallozzi, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of sports medicine and physical fitness*, *49*(1), 6.

Stefanyshyn, D. J., Nigg, B. M., Fisher, V., O'Flynn, B., & Liu, W. (2000). The influence of high heeled shoes on kinematics, kinetics, and muscle EMG of normal female gait. *Journal of Applied Biomechanics*, *16*(3), 309-319.

Stefanyshyn, D. J. a. B. M. N. (2000). Work and Energy Influenced by Sports Equipment. *Biomechanics and Biology of Human Movement, Editors BM Nigg, BR MacIntosh and J.Mester.Human Kinetics, Champaign, ILHuman Kinetics, Champaign, IL*, 49-65.

Tam, N., Tucker, R., Santos-Concejero, J., Prins, D., & Lamberts, R. P. (2019). Running economy: neuromuscular and joint-stiffness contributions in trained runners. *International journal of sports physiology and performance*, *14*(1), 16-22.

Thomson, R., Birkbeck, A., Tan, W., McCafferty, L., Grant, S., & Wilson, J. (1999). The modelling and performance of training shoe cushioning system. *Sports engineering*, *2*, 109-120.

Turner, A. M., Owings, M., & Schwane, J. A. (2003). Improvement in running economy after 6 weeks of plyometric training. *The Journal of Strength & Conditioning Research*, *17*(1), 60-67.

Warne, J. P., Moran, K. A., & Warrington, G. D. (2015). Eight weeks gait retraining in minimalist footwear has no effect on running economy. *Human movement science*, *42*, 183-192.

Wei, C., Yu, L., Duncan, B., & Renfree, A. (2020). A plyometric warm-up protocol improves running economy in recreational endurance athletes. *Frontiers in physiology*, *11*, 197.

Whipp, B. J., & Wasserman, K. (1969). Efficiency of muscular work. *Journal of applied physiology*, *26*(5), 644-648.

Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of applied physiology*, *63*(3), 1236-1245.

Wilson, J. M., Hornbuckle, L. M., Kim, J.-S., Ugrinowitsch, C., Lee, S.-R., Zourdos, M. C., Sommer, B., & Panton, L. B. (2010). Effects of static stretching on energy cost and running endurance performance. *The Journal of Strength & Conditioning Research*, *24*(9), 2274-2279.

Worobets, J., Wannop, J. W., Tomaras, E., & Stefanyshyn, D. (2014). Softer and more resilient running shoe cushioning properties enhance running economy. *Footwear Science*, *6*(3), 147-153.

Yamamoto, L. M., Lopez, R. M., Klau, J. F., Casa, D. J., Kraemer, W. J., & Maresh, C. M. (2008). The effects of resistance training on endurance distance running performance among highly trained runners: a systematic review. The Journal of Strength & Conditioning Research, 22(6), 2036-2044. Warreyn, P., Ruysschaert, L., Wiersema, J.R., Handl, A., Pattyn, G., Roeyers, H., 2013.

Infants' mu suppression during the observation of real and mimicked goal-directed actions. Dev. Sci. 16, 173–185, http://dx.doi.org/10.1111/desc. 12014.

Woodruff, C.C., Martin, T., Bilyk, N., 2011. Differences in self- and other-induced Mu suppression are correlated with empathic abilities. Brain Res. 1405, 69–76, http://dx.doi.org/10.1016/j.brainres.2011.05.046.