Economy of running

Biomechanical research for running economy

We would like to discuss about past researches of running economy on their findings and problems. Recently there have been a lot of papers about the relationship between running economy and training, but they haven't explained the mechanical factors of influence in running economy. Motion sensors and the other devices to monitor running mechanics have been developed, so we have a good opportunity to study how biomechanical factors will affect running economy in various situations. The speakers who have studied running economy thoroughly will show original research findings and ideas about running economy and suggest future directions.

This session is supported by CASIO Computer Co., Ltd, which has developed a motion sensor and its analyzing software especially for distance running with Dr. Enomoto. So CASIO might have a short presentation about the motion sensor for running in the session.

Organizer

Dr. Yasushi Enomoto

He has studied biomechanics of distance running. He has been recently focusing not only on biomechanical factors, but also physiological and training factors affecting running economy and performance. Especially he has developed this motion sensor and its software with the CASIO to evaluate the distance running technique. He is a coach at the track and field club in Tsukuba University and is a dedicated member of the scientific committee and a national coach of middle distance running of JAAF.

Invited Speakers

Dr. Heikki Kyröläinen

Heikki Kyröläinen, PhD, is a Professor in the Department of Biology of Physical Activity, University of Jyväskylä, Finland. He was found competent for professorships in Exercise Physiology in 2003, Biology of Physical Activity in 2005,
Kinesiology in 2006, and Biomechanics in 2007. He has published over 140 peer-reviewed international scientific papers and about 250 chapters in books, abstracts, proceedings, and domestic publications. His research interests are wide in the field of biology of physical activity but, however, a major research line has been mechanical efficiency and economy during human locomotion since 1987. In addition to science, he is working in practice as a coach of long and triple jumpers.

**Dr. Chris Arellano**

Christopher J. Arellano has a broad interest in understanding the biomechanics and energetics of both human and animal locomotion. Dr. Arellano’s doctoral research focused on human locomotion emphasizing medio-lateral foot placement and arm swing as primary balance control strategies. He is currently a Postdoctoral Research Associate in the department of Ecology and Evolutionary Biology at Brown University. His current research examines the significance of muscle-tendon shape change across an array of locomotor behaviors by making direct measurements that link mechanics, function, and performance.

**Dr. Gary Heise**

Gary Heise is a Professor in Biomechanics and the director of the School of Sport and Exercise Science at the University of Northern Colorado (USA). He earned his Ph.D. from Penn State University (advisor: Richard C. Nelson) and his M.S. from Arizona State University (advisor: Philip E. Martin).
EVALUATION OF RUNNING MECHANICS USING MOTION SENSOR FOR DISTANCE RUNNERS

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Institute of Health and Sport Sciences, University of Tsukuba, Tsukuba, Japan²

The purpose of this presentation is to show three cases of standard test to evaluate running motion on a 400m track, presenting the relationship of O2 consumption with the running motion at a treadmill test, and running motion during a distance race, and to discuss the effectiveness of motion sensor as a tool for training and coaching in running. These studies show that it might be useful to evaluate running motion by comparing running parameters of standard test to real race. Furthermore, the evaluation has a possibility to give criteria for training and a prediction of the race performance to a runner and a coach.

KEY WORDS: accelerometer, oxygen consumption, running motion, performance

INTRODUCTION: Running economy and mechanics are important factors in distance running performance for a wide range of distance. It has been studied using biomechanical methods (Williams and Cavanagh, 1987; Heise and Martin, 2001; Arellano and Kram, 2014). However, those studies have been done by separate measurements of O2 consumption and running mechanics measured only in one running cycle. It seems that running economy varies by individuals, running speed, fatigue and condition of the day. Motion sensor implemented with 3 dimensional accelerometer, gyro and geomagnetic sensors which has been developed to be small and sophisticated enough to attach to the body without obstructing human movement, which might be useful to measure running mechanics in practical use.

The specification of the motion sensor used in this study is shown in Table 1 and 2. It is small enough to attach to the body during running and designed to attach on top of the sacrum with running shorts or tights. Figure 1 shows a schematic example of a motion sensor attached to the body. Table 2 shows the dynamic range and sampling frequency of the sensor.

The purpose of this presentation is to show three cases of standard test to evaluate running motion on a 400m track, presenting the relationship of O2 consumption with the running motion at a treadmill test, and running motion during a distance race, and to discuss effectiveness of motion sensor as a tool for training and coaching in running.

Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Size and weight of sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Size</td>
<td>41.5x55.3x9.55mm</td>
</tr>
<tr>
<td>2. Weight</td>
<td>31.7g</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Item</th>
<th>Acceleration</th>
<th>Gyro</th>
<th>Magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Dynamic range</td>
<td>+/-16g</td>
<td>+/-2000dps</td>
<td>+/-1.9gauss</td>
</tr>
<tr>
<td>2. Sampling frequency</td>
<td>200Hz</td>
<td>200Hz</td>
<td>16Hz</td>
</tr>
</tbody>
</table>

METHODS: The sensor can estimate running parameters, which are running cycle time, step frequency, contact time and vertical oscillation from raw data with the original developed software. Table 3 shows standard error and residual error for each parameter. They are
compared with photo sensor (Optojump, Microgate) for cycle time, with motion analysis of video (Frame DIAS-V, DKH) for vertical oscillation and angle of the sensor, and with force platform (KISTLER) for contact time. Each error is calculated by following equation:

\[
\text{Standard error} = \frac{\sum_{i=1}^{n} (X_i - T_i)}{n}
\]

\[
\text{Residual error} = \frac{\sum_{i=1}^{n} (X_i - T_i)}{n}
\]

\( n \) : Number of measurement sample  
\( X_i \) : Reference data  
\( T_i \) : Sensor estimate data

All parameters are evaluated as typical one cycle averaged from 10 cycles. Especially total impulse (TI, N/kg/min) is calculated by integration of acceleration during typical one cycle (N/kg) multiplied by cycle frequency (cycles/min).

At the treadmill test, the O2 consumption was measured in the last 30sec during 3min running. The running speed gradually increased from 3.4m/s to 5.5m/s during 5 or 6 times of treadmill running based on their lactate threshold (LT).

The standard test for evaluating running motion was designed to estimate training criteria for 5000m race. The subject runs seven sets each of 800m distance at a constant running speed. The running speed of each set was increased gradually between a short rest. Lactate threshold (LT) pace was set for 3rd round and race pace of target time was set for 5th round. If a subject set a goal of 14min 10sec for next 5000m race, the 400m pace of the test would be recommended at 92, 84, 76, 72, 68, 64, 60sec for each set of 800m.

At race measurement, the motion sensor was attached to the body of each subject and the parameters were measured in real races.

**RESULTS & DISCUSSION:** Figure 2 shows the relationship of VO2 with TI for typical subjects. It shows that there are high correlation coefficients in linear expression between VO2 and TI for all of the subjects. Several studies show that running economy is influenced by ground reaction force and movement of CG of the body. It is suggested that TI might be one of critical factor for individual running cost.
From the result of the standard running test, Figure 3 shows changes in running parameters to running speed for typical subjects. It shows linear increase in step frequency and step length to running speed but decrease in vertical oscillation. Inter individual variability of TI was greater than other parameters. The recent 5000m race results of these subjects were Subject A 14’33”, B 14’53”, C 14’58”, D 15’09”, E 16’13”, and F 16’35”. Good runner shows smaller TI than poor runner at same speed. In spite of linear relationship tendencies of running speed and step length, in some cases support length and non-support length have inflection points around their race speed, and furthermore, there are rapid increases of TI around the race speed on several subjects. It implies that those inflection points might be recognized as threshold for estimating race pace from running motion and the possibility to improve the running performance.

Figure 4 shows an example of changes in running speed and step frequency to distance during a race for a typical subject. The running speed decreased at 3800m and finished in 14min 33sec.
Figure 5 shows each running parameters against running speed. Black line indicates his average value in standard running test. Vertical oscillation and TI were greater than standard value from initial stage of the race. It is clear that step length in support phase normalized to the body height were greater in the last 1000m than the previous 4000m. It could be speculated that subject A ran in less efficient motion from the beginning of the race than usual and it caused fatigue in the latter half of the race, then running motion dramatically changed and running speed decreased at the end of the race. These results suggest that a series of analysis using motion sensor for the runner might be useful to evaluate what happened in the race and what can be done in the future training to prepare for the next race.

CONCLUSION:
The motion sensor developed to evaluate running motion has shown good availability for practical use. The step parameters are used to evaluate basic running mechanics with running speed and total impulse of the acceleration is one of the correlative factors to evaluate running economy for each runner. It might be necessary for standard running test and submaximal treadmill test to evaluate each runner by measuring running parameters before a race.

REFERENCES:
RUNNING ECONOMY IS A MULTIFACTORIAL PHENOMENON

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The purpose of this review was to describe economy of human locomotion, especially in running. Several factors such as age, sex, air resistance, body temperature, body weight, maximal aerobic capacity, muscle fibre distribution, vertical oscillation of the body, ground reaction forces and their directions, tendomuscular structure, training status, and fatigue have been demonstrated to affect running economy (RE). Although there exist interindividual differences in RE, training, especially strength and power training, improves RE to a certain degree. On the contrary, RE decreases in fatiguing conditions, but negative influences on RE can be minimized by optimal training.

KEY WORDS: running, training, fatigue.

INTRODUCTION: Muscular exercises seldom involve pure forms of isolated isometric, concentric or eccentric actions. This is because the body segments are periodically subjected to impact forces, as in running or jumping, or because some external force such as gravity lengthens the muscle. In most human motions, skeletal muscles act through a stretch-shortening cycle (SSC) (Norman and Komi, 1979), which may enhance the mechanical outputs of the muscle and, therefore, the logical consequence should be that work efficiency is also enhanced.

Marey and Demeny wrote already in 1885 as follows: "If we perform two successive vertical jumps exerting each time our maximal effort, it always happens that the second jump is higher than the first one. The storage of work in the tense muscles gives to it, since beginning of the second jump, a very high elastic force which on the contrary was developed only gradually by the muscle during the first jump". Over a hundred years later their observations have been used to evaluate the contribution of elastic energy in human locomotion (Asmussen and Bonde-Petersen 1974; Cavagna 1977; Kaneko et al 1984).

To start the discussion on efficient and economical movement of SSC actions, various definitions need to be addressed briefly. Mechanical efficiency (ME) incorporates two processes, phosphorylation coupling and contraction coupling, in converting energy from one form to another (Whipp and Wasserman, 1969). In an isolated situation, muscular efficiency is about 28%. Mechanical work is missing from the determination of the term economy, but submaximal oxygen uptake per unit body mass required to perform a certain task is widely accepted as the physiological criterion for efficient movement. The purpose of this short review was to describe running economy (RE) and factors affecting it. In particular, the roles of training and fatigue in RE were emphasized.

RUNNING ECONOMY: In running, values of ME have varied enormously (from 19 to 80%) depending on the methods used to measure and calculate mechanical work and energy expenditure (e.g. Cavagna et al. 1965; Margaria 1968; Asmussen & Bonde-Petersen 1974; Cavagna & Kaneko 1977; Ito et al 1983). Various factors such as age (e.g. Daniels et al. 1978), sex (e.g. Bransford & Howley 1977), air resistance (e.g. Costill & Fox 1969), body temperature (e.g. Rowell et al. 1969), body weight (e.g. Cureton et al. 1978), maximal aerobic
power (e.g. Mayhew 1977), and muscle fibre distribution (e.g. Bosco et al. 1987; Kyröläinen et al. 2003) have been found to affect running efficiency / economy.

It has also been suggested that biomechanical factors may account for a substantial portion of variations in RE. As compared to a less successful runner, a faster endurance runner is characterized by less vertical oscillation (Gregor & Kirkendall 1978), longer strides (Hoshikawa et al. 1971; Cavanagh & Williams 1982), less change in velocity during ground contact (Kaneko et al. 1985), and lower first peak in the vertical component of the ground reaction force associated with a tendency towards smaller anteroposterior peak forces (Williams & Cavanagh 1987). It has also been shown that less economical runners exhibit greater total and net vertical impulses, while other parameters of ground reaction forces are not associated with RE (Heise & Martin 2001). Furthermore, there are runner, shoe and surface interactions. For example, Roy and Stefanyshyn (2006) found that higher shoe midsole longitudinal bending stiffness was associated with improved RE.

Interindividual variations demonstrate that subjects trained in endurance running are more economical than their untrained counterparts (Bransford & Howley 1977), while intraindividual variation in RE reportedly varies between 2 and 11% (Morgan et al. 1989). Figure 1 shows RE among middle-distance runners at different running speeds. It shows nicely that a runner who is economical at a given running speed will usually be economical at other speeds as well (Williams 1990; Kyröläinen et al. 2003), and the interactions between mechanical and metabolic variables appear to be very complex (Mayhew 1977; Lake & Cavanagh 1996; Kyröläinen et al. 2003). However, a puzzling question is: what are the factors that explain differences in running economy?

In recent years, studies attempting to explain differences in RE have concentrated on muscle mechanics. Arampatzis et al. (2006) found that the most economical runners showed higher contractile strength and higher normalized tendon stiffness (ratio between tendon force and strain) in the triceps surae muscle-tendon unit and a higher compliance of the quadriceps tendon and aponeurosis at low tendon forces. Kunimasa et al. (2014) and Sano et al. (2015) compared Kenyan and Japanese runners. They observed that elite Kenyan runners had longer Achilles tendons and tendon moment arms, which may result in the reduction of Achilles tendon strain and medial gastrocnemius (MG) muscle activation, and therefore lower oxygen consumption requirements. As a consequence, this may allow MG fascicles to work
more isometrically during the contact phase of running. Among Kenyan distance runners, Mooses et al. (2015) also found that Achilles moment arm length was associated with better RE. In addition, they observed that longer leg length, but not RE, was related to better running performance, suggesting that RE can be compensated by other factors.

**TRAINING AND ECONOMY:** It is quite well documented that strength training not only improves RE but also muscle power and performance (Beattie et al. 2014). For example, Millet et al. (2002) studied triathletes who trained for 14 weeks. They found that the group who also did two heavy weight training sessions in a week improved their RE, which was not the case in the endurance-only group. In the study of Storen et al. (2008), 8 well-trained runners performed half-squats (4x4 repetitions) 3 times per week for 8 weeks, and their 7 counterparts trained only endurance. The intervention group improved RE by 5.0%, maximal force by 33.2%, rate of force production by 26.0%, and time to exhaustion by 21.3%.

Albracht and Arampatzis (2013) studied the effects of 14-weeks of strength training of the plantarflexor muscles on tendon-aponeurosis stiffness and contractile strength, and their associations with RE. They observed enhanced RE after increasing triceps surae tendon stiffness and contractile strength, which may indicate that force generation during running became more economical within the lower extremities due to higher energy storage and release in the series elastic elements of the triceps surae.

**FATIGUE AND ECONOMY:** There are several factors that may reduce RE in fatiguing conditions. 1) Metabolic factors, including changes in energy sources during running that has been shown to cause a reduction of 0.07 in respiratory exchange ratio and a shift to fatty acid oxidation (Kyröläinen et al. 2000). In addition, body temperature regulation requires energy (Saltin et al. 1966), and microstructural muscle damage consisting of increased cytokines may decrease RE (Kyröläinen et al. 2000). 2) Mechanical factors refer to changes in running technique such as an increase in stride frequency, a decrease in stride length (Morin et al. 2011), and possible changes in contact times, vertical displacements of the body, and changes in arm movements. 3) Neuromuscular factors have also been shown to change during prolonged running. Maximal activation of the leg extensor muscles decreases (Avela et al. 1999) but in submaximal running EMG activity increases (Komi et al. 1986) due to the recruitment of more motor units and an increase of their firing frequency.

**CONCLUSION:** RE is a multifactorial phenomenon, and it cannot solely be explained by mechanical factors. The complex links between utilization of different energy sources, thermoregulation, body composition, tendomuscular structure, muscle activation and damage should be studied. The good news is, however, that optimal training makes it possible to improve RE.

**REFERENCES:**


HOW BIOMECHANICAL IMPROVEMENTS IN RUNNING ECONOMY COULD HELP BREAK THE 2-HOUR MARATHON BARRIER

Christopher J. Arellano¹, Wouter Hoogkamer², and Rodger Kram²

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University of Colorado, Boulder, CO, USA²

A sub-2-hour marathon requires an average velocity that is “only” 2.5% faster than the current world record of 2:02:57. A 2.5% reduction in the metabolic cost of running would enable a 2.5% faster velocity of 5.86 m/s, i.e. a sub-2-hour marathon. Our analyses suggest that the metabolic cost of body weight support could be reduced by running at the equator (slightly lower gravity ~9.78 m/s²) and by pre-emptive, strategic dehydration of 2% body weight. Drafting and tailwinds could reduce the cost of forward propulsion. These biomechanical factors could each be exploited to enhance running economy by small amounts, and sum to save at least 178 seconds, permitting a time of 1:59:59.

KEYWORDS: metabolic cost, locomotion, speed, efficiency,

INTRODUCTION: When Dennis Kimetto ran the current 42.195km marathon record of 2:02:57 in Berlin in 2014, the possibility of a sub-2 hour marathon generated great excitement. A 2-hour marathon “only” requires an average velocity that is 2.5% faster. Running economy, the metabolic energy required to run at a specific speed, is a key determinant of distance-running performance. Improving running economy allows an athlete to run at a proportionally faster speed while consuming metabolic energy at the same rate. A 2.5% reduction in the metabolic cost of running at 5.72 m/s would enable a 2.5% faster velocity of 5.86 m/s, i.e. a sub-2-hour marathon. Here, we explore where a 2.5% improvement in running economy could be gained by enhancing different aspects of running biomechanics. Approximately 80% of the metabolic cost of human running, on level ground, can be explained by the synergistic tasks of body weight support and forward propulsion (Arellano and Kram, 2014). Leg swing, and lateral balance can explain 7% and 2%, respectively. Below, we describe several ways in which running economy can be improved by reducing the metabolic cost for several of these biomechanical task.

BODY WEIGHT SUPPORT: Reducing the cost of supporting body weight (BW) provides the biggest opportunity. Pulling upward on the body reduces metabolic cost in slightly less than direct proportion (Farley and Mcmahon, 1992; Teunissen et al., 2007).

Permissible: Typically, body mass and weight are intrinsically linked. However, body weight can be altered independently by changing gravitational acceleration. At the equator, the gravitational acceleration is about 0.31% less (9.78m/s²) than in Berlin. Assuming that supporting body weight explains ~74% of the metabolic cost of running (Teunissen et al., 2007), a 0.31% smaller gravitational acceleration could result in a metabolic savings of 0.23% during running, translating into a 17 second faster marathon time. Elite marathon runners are already extremely lean, however, strategic dehydration would reduce body weight and may provide benefits. Elite runners can lose ~8.8%BW during a marathon (Beis et al. 2012) and still reach peak performance. On a cold day, a runner could preemptively dehydrate by 2% body weight and then drink throughout the race to avoid dehydration levels that would impair performance. Dehydrating by 2% body weight prior to the marathon could improve running economy by 1.5%, translating into a 108 second faster marathon time. Related to the cost of body weight support is the cost of cushioning. Shoe cushioning properties can enhance running economy and are permissible under the International Association of Athletics Federations (IAAF) rules. Tung et al. (2014) showed that running barefoot on a cushioned treadmill surface of 10mm of foam saves 1.6% energy as compared to running on a rigid non-cushioned surface.

Prohibited: Grabowski and Herr (2009) developed carbon-fiber spring exoskeletons worn in parallel with the legs. They reduced the metabolic cost of hopping by 24%. Just a 3.4%
reduction in the need to generate body-weight support would enable a 2.5% reduction in metabolic cost. However, exoskeleton mass would increase the metabolic cost of leg swing. Furthermore, IAAF rule 144.3d seems to prohibit the use of wearable springs. Optimizing cushioning and energy return properties of the running surface could provide dramatic savings in metabolic energy. Kerdok et al. (2002) built a treadmill with a vertically compliant bed (surface deflection of ~2 cm) with minimal damping that reduced the metabolic cost of running by as much as 12%. The decreased surface stiffness likely allows for running with less knee flexion, resulting in smaller knee joint muscle-moments required for supporting body weight and thus reducing metabolic cost. However, IAAF rule 240.2 specifies that for record purposes, a marathon must be run on a road surface.

FORWARD PROPULSION: Reducing the cost of forward propulsion provides the second greatest opportunity for improving running economy. During the second-half of ground contact, the runner must generate a propulsive impulse to maintain a steady speed. **Permissible:** At 5.72 m/s, air resistive force is ~10 N (Kyle and Caiozzo, 1986) for a 58kg elite runner like Kimetto. Chang and Kram (1999) showed that only a small reduction in propulsive impulse of 4% BW*s is needed to reduce metabolic cost by 2.5%. Data from Kyle and Caiozzo (1986) suggest that overcoming air resistance at a speed of 5.72 m/s exacts a metabolic cost of ~1 W/kg. Drafting 1 m behind another runner can reduce air resistance by 93% (Pugh, 1971). Reducing air resistance by 50% would improve running economy by 0.52 W/kg, i.e. the 2.5% needed to facilitate a marathon time of 1:59:59. It is not trivial, however, to find sacrificial runners who could provide drafting at 5.86 m/s for more than 21.1km.

Running with a tailwind could reduce the cost of forward propulsion, yet, IAAF rule 260.21b make it impossible to run a full marathon with a tailwind, since the start and finish must be within 21.1km measured along a theoretical straight line. An optimal racecourse might be a 21.1km loop with drafting, reaching the halfway mark at 1:00:00, followed by a 21.1km straight section with a tailwind. In addition, such an initial loop could benefit from shielding via a forest, buildings or natural valleys. **Prohibited:** Running downhill reduces metabolic cost compared to level running. The optimum gradient is -20% (Minetti et al., 2002); however, a marathon record can only be ratified on a course with a net downhill change of less than 42.2 meters. For a marathon, a 42.2 meter loss of elevation is equivalent to a -0.1% gradient, allowing for a small reduction in metabolic cost and facilitating a 0.5% increase in speed that would save 37 seconds at world record pace. Holding all other factors constant, we estimate from Minetti et al.’s (2002) regression equation that running downhill at a gradient of just -0.47%, equivalent to a net elevation loss of 198.34 m, would allow a marathon time of 1:59:59.

Running with a passive exoskeleton is another possibility for reducing the cost of forward propulsion. Recently, Collins et al. (2015) designed an unpowered elastic ankle exoskeleton with a clutch that improved walking economy by 7.2%. They found that with the appropriate spring stiffness, mechanical energy could be temporarily stored and then released to contribute to the overall propulsive power generated at the ankle joint. This device has not yet been developed for running, but we are intrigued by the idea that similar design principles could be applied to assist with forward propulsion during running and possibly reduce metabolic cost by the 2.5% required to achieve a sub-2-hour marathon, but again, IAAF rule 144.3d seems to prohibit the use of wearable springs.

LEG SWING: In our experiments, the task of swinging the legs comprises only about 7% to the net metabolic cost of running (Arellano and Kram, 2014). However, adding mass to the legs has been shown to greatly increase the metabolic cost of running (Frederick et al., 1984; Franz et al., 2012). Since the distal parts of the legs (feet) accelerate and decelerate faster than proximal parts (thighs), adding mass to distal parts of the leg has a larger effect on metabolic cost (Martin, 1985). Frederick et al. (1984) showed that adding 100 gram of mass per shoe increased the metabolic cost of running by ~1%. Franz et al. (2012) confirmed those classic findings using modern, very lightweight racing flats. In a follow-up study, Hoogkamer et al. (2016) recently showed that increases in the metabolic cost of
running induced by adding mass to the shoes, translated directly to changes in 3k-time trial performance.

**Permissible:** Assuming a US size 10 (EU 43), each shoe that Kimetto wore during his 2.02.57 marathon had a mass of ~230 grams. A decrease of 100 grams per shoe would reduce the metabolic cost of running by 1%, therefore, a hypothetical shoe of zero mass (as opposed to 230 gram racing flats) could facilitate a 2.3% faster marathon time of ~2:00:11. Yet, there are indications that the change of 1% per 100 gram of mass per shoe is actually speed dependent and smaller at higher speed (Frederick et al., 1984; Hoogkamer et al., 2016). Furthermore, Tung et al. (2014) have shown that if shoe mass is reduced by eliminating cushioning, there is no net reduction in the metabolic cost of running.

**Prohibited:** The observation that the metabolic cost of running is more sensitive to mass added at distal segments of the limb, together with the observation that many elite African runners have slender calves, has led some sport scientists to suggest that the exceptional economy of East African runners is related to their calf anatomy (Saltin et al., 1995). Along this line of reasoning, one could argue that replacing one’s lower legs by lightweight running-specific prostheses could reduce leg swing cost. The mass of a lower leg with a running prosthesis has been estimated to be 3kg versus 5.8kg for a biological leg (Brüggemann et al., 2008). By focusing on the metabolic cost of swinging the legs, it appears that running with prostheses could be more economical. Myers and Steudel (1985) added 1.8kg to each shank and observed a ~12% increase in metabolic cost. Combining these observations, one could expect an 18.7% improvement in running economy by replacing biological legs with lighter running-specific prostheses. However, since leg swing only explains 7% of the metabolic cost of running (Arellano and Kram, 2014), saving >7% seems improbable. Furthermore, intact biological lower legs with ankle joints and elastic tendons and ligaments have beneficial functions in running. Although data on the metabolic cost for running with running-specific prosthesis after bilateral transtibial amputations is scarce, the available data indicates that running with running-specific prostheses is not more economical than in able-bodied runners (Beck et al., 2015; Weyand et al., 2009).

**CONCLUSION:** Feasible and legal biomechanical approaches (reduced gravity, preemptive dehydration, tailwind) could each be exploited to enhance running economy by small amounts and therefore permit a sub-2 hour marathon. These approaches are permissible under IAAF rules but would require a concerted effort by race directors, cooperative athletes, and optimal meteorological conditions.
REFERENCES:
THE WORK AND ACTIVATION OF LOWER EXTREMITY MUSCLES IN EXPLAINING INTERINDIVIDUAL VARIABILITY IN RUNNING ECONOMY

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The purpose of this study was to describe the relationships between RE and the neuromechanics of ground contact. Results of biomechanical studies suggest that more economical runners use different neuromuscular strategies during the stance phase of running. Research in our lab revealed significant, positive correlations between metabolic cost and positive work at the hip and ankle, but significant, negative correlations between metabolic cost and positive work at the knee. Studies focusing on RE and muscle activation patterns show contrasting results. Mechanics may suggest straightforward applications to training and coaching, but further study is required in the area of muscle activation.

KEY WORDS: running economy, mechanics, EMG, activation, coactivation

The work of Conley & Krahenbuhl (1980) provided the impetus for research in running economy (RE). They showed conclusively that among a group of homogenous runners (i.e., runners with similar VO2max), RE was significantly related to race performance. Thus, why some runners are more economical than others, especially when examining runners of similar fitness levels, became an important performance question. Keith Williams completed a comprehensive study in 1980, which spawned several publications, and showed that several biomechanical variables help explain the interindividual variability in RE. The research described in this presentation will focus on how runners interact with the ground during the stance phase of running and the relationships between RE and the neuromechanics of ground contact.

Our work with ground reaction force (GRF) characteristics (Heise & Martin, 2001), was influenced by Kram & Taylor's research (1990). They focused on animals representing a wide range of body mass, whereas we studied a homogenous group of human runners. Kram and Taylor suggested that the force required to support a running animal and the time course of that force determine the metabolic cost of running. We showed that less economical humans (higher metabolic cost) exhibited greater total and net vertical impulses, but other GRF characteristics were not related to metabolic cost. These results, combined with our findings showing significant relationships between RE and lower extremity mechanical work (Heise, Smith, & Martin, 2011), led us to study how runners produce these forces during ground contact and thus we focused on muscle activation patterns. Regarding the results of joint mechanical work during stance, we showed significant, positive correlations between metabolic cost and positive work at the hip and ankle, but significant, negative correlations between metabolic cost and positive work at the knee.

Overall, mechanical results highlighted here, and findings of others, suggest that more economical runners use different muscle activation strategies during the stance phase of running. In two separate samples (Heise, Morgan, Hough, & Craib, 1996; Heise, Shinohara, & Binks, 2008), we showed significant, negative relationships between metabolic cost and select measures of muscle activation and coactivation during stance. In other words, economical runners activated certain muscles (or pairs of muscles) for longer durations during stance. This counterintuitive result had implications regarding dynamic leg stiffness during stance and tissue stiffness in general. Recently, however, Moore et al. (2014) presented results in direct contrast with ours; they found metabolic cost to be positively associated with muscle activation durations. To add further uncertainty to this topic of inquiry, we recently reported no correlations between metabolic cost and muscle activation duration using an approach similar to Moore’s group, but we did notice different trends between men and women.
(Schornstein et al. 2015). Current research in our lab is addressing methodologic differences among researchers which may explain these contrasting results centered on RE and muscle activation during stance.

From an applied perspective, the implications from our work examining mechanical and neuromuscular output of the lower extremity musculature during running may inform training decisions made by distance runners and their coaches. Our research findings on RE and mechanical work at the joints of the lower extremity indicate that more economical runners maximize positive work at the knee and minimize positive work at the hip and ankle during stance. This may lead to a greater strength training focus on musculature crossing the knee, but the contribution of two-joint muscles, especially those that cross the knee (e.g., rectus femoris, medial hamstrings, gastrocnemius) must be considered. Research on muscle activation during stance suggest that neuromuscular solutions to optimal mechanical output may be more individual. Therefore, more focus on these neuromuscular solutions must be pursued.

REFERENCES:

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The author thanks his mentors, Dr. Richard Nelson and Dr. Phil Martin, colleague Dr. Jeremy Smith, and his graduate students for their help and inspiration on this research topic.