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

Christopher J. Arellano[1], Wouter Hoogkamer[2], and Rodger Kram[2]

Brown University, Providence, RI, USA[1]
University of Colorado, Boulder, CO, USA[2]

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/s^2) 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/s^2) 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 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).

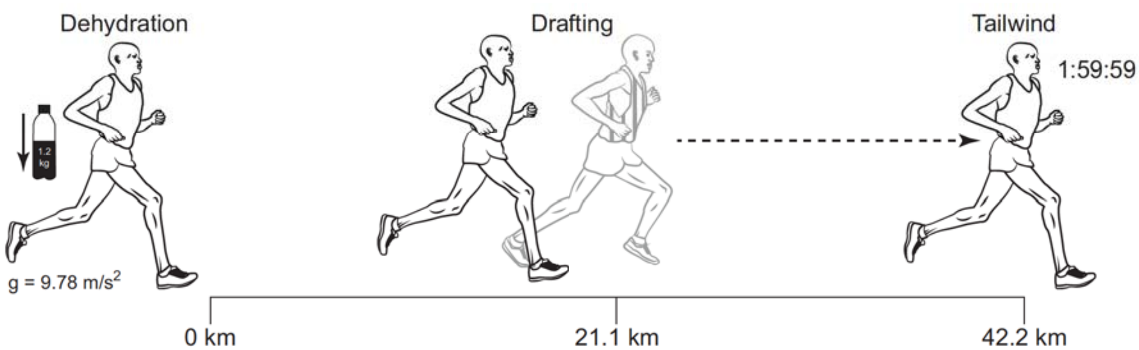

Figure 1. The current record indicates that only a 2.5% improvement in running economy is needed to break the sub-2-hour marathon barrier, which could be achieved by reducing the metabolic cost of body weight support and forward propulsion. An elite marathoner like Kimetto can reduce the cost of body weight support by running close to the equator (lower gravity) and by preemptively and strategically dehydrating (2% body weight). In addition, Kimetto could reduce the cost of forward propulsion by optimally drafting during the first 21.1 km and then under optimal conditions, take advantage of a straight section tailwind during the last 21.1km.

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:

Arellano, C. J. and Kram, R. (2014). Partitioning the metabolic cost of human running: A task-by-task approach. *Integrative and Comparative Biology* 54, 1084-98.

Beck, O. N., Taboga, P. and Grabowski, A. M. (2015). Lower prosthetic stiffness minimizes the metabolic cost of running for individuals with bilateral leg amputations. In *American Society of Biomechanics*. Columbus, Ohio.

Beis, L. Y., Wright-Whyte, M., Fudge, B., Noakes, T. and Pitsiladis, Y. P. (2012). Drinking behaviors of elite male runners during marathon competition. *Clinical Journal of Sport Medicine* 22, 254-61.

Brüggemann, G. P., Aramptzis, A., Emrich, F. and Wolfgang, P. (2008). Biomechanics of double transtibial amputee sprinting using dedicated sprinting prostheses. *Sports Technology* 1, 220-227.

Chang, Y. H. and Kram, R. (1999). Metabolic cost of generating horizontal forces during human running. *Journal of Applied Physiology* 86, 1657-62.

Collins, S. H., Wiggin, M. B. and Sawicki, G. S. (2015). Reducing the energy cost of human walking using an unpowered exoskeleton. *Nature* 522, 212-5.

Farley, C. T. and Mcmahon, T. A. (1992). Energetics of walking and running: Insights from simulated reduced-gravity experiments. *Journal of Applied Physiology* 73, 2709-12.

Franz, J. R., Wierzbinski, C. M. and Kram, R. (2012). Metabolic cost of running barefoot versus shod: Is lighter better? *Medicine & Science in Sports & Exercise* 44, 1519-25.

Frederick, E. C., Daniels, J. T. and Hayes, J. W. (1984). The effect of shoe weight on the aerobic demands of running. In *Current topics in sports medicine*, eds. N. Bachl L. Prokop and R. Suckert), pp. 616-625. Vienne (Austria): Urban & Schwarzenberg.

Grabowski, A. M. and Herr, H. M. (2009). Leg exoskeleton reduces the metabolic cost of human hopping. *Journal of Applied Physiology* 107, 670-8.

Hoogkamer, W., Kipp, S., Spiering, B. A. and Kram, R. (2016). Altered running economy directly translates to altered distance-running performance. *Medicine & Science in Sports & Exercise*, under review.

Kerdok, A. E., Biewener, A. A., Mcmahon, T. A., Weyand, P. G. and Herr, H. M. (2002). Energetics and mechanics of human running on surfaces of different stiffnesses. *Journal of Applied Physiology* 92, 469-78.

Kyle, C. R. and Caiozzo, V. J. (1986). The effect of athletic clothing aerodynamics upon running speed. *Medicine & Science in Sports & Exercise* 18, 509-15.

Martin, P. E. (1985). Mechanical and physiological responses to lower extremity loading during running. *Medicine & Science in Sports & Exercise* 17, 427-33.

Minetti, A. E., Moia, C., Roi, G. S., Susta, D. and Ferretti, G. (2002). Energy cost of walking and running at extreme uphill and downhill slopes. *Journal of Applied Physiology* 93, 1039-46.

Myers, M. J. and Steudel, K. (1985). Effect of limb mass and its distribution on the energetic cost of running. *Journal of Experimental Biology* 116, 363-73.

Pugh, L. G. (1971). The influence of wind resistance in running and walking and the mechanical efficiency of work against horizontal or vertical forces. *Journal of Physiology* 213, 255-76.

Saltin, B., Larsen, H. and Terrados, N. (1995). Aerobic exercise capacity at sea level and at altitude in kenyan boys, junior and senior runners compared with scandinavian runners. *Scandinavian Journal of Medicine & Science in Sports* 5, 209-221.

Teunissen, L. P., Grabowski, A. and Kram, R. (2007). Effects of independently altering body weight and body mass on the metabolic cost of running. *Journal of Experimental Biology* 210, 4418-27.

Tung, K. D., Franz, J. R. and Kram, R. (2014). A test of the metabolic cost of cushioning hypothesis during unshod and shod running. *Medicine & Science in Sports & Exercise* 46, 324-9.

Weyand, P. G., Bundle, M. W., Mcgowan, C. P., Grabowski, A., Brown, M. B., Kram, R. and Herr, H. (2009). The fastest runner on artificial legs: Different limbs, similar function? *Journal of Applied Physiology* 107, 903-11.