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NARRATIVE REVIEW

Biomechanical Alterations during Aquatic Treadmill Running

Nicholas J. Held^{1,2,3}, Christopher L. MacLean³, and Darren E. R. Warburton^{1,2,*}

Abstract

Background: Water running, and more specifically aquatic treadmill (ATM) running, has become increasingly popular as part of the rehabilitation of injuries and as a means of cross-training. **Purpose:** The primary purpose of this narrative review was to discuss the kinematic, kinetic, spatiotemporal, and muscle activation differences between ATM and land treadmill running. A secondary purpose was to examine the possible benefits and limitations of applying an ATM running intervention as a means for returning to run or sport were discussed. **Methods:** A critical appraisal of the current literature revealed a series of studies related to ATM training and/or rehabilitation. **Findings:** Water provides a unique training and rehabilitation environment owing to the fluid forces acting upon the body during immersion. A growing body of evidence supports the safety and efficacy of ATM for both training and rehabilitation purposes. Current evidence indicates that ATM running does not result in differential biomechanical adaptations in comparison to land treadmill running. **Conclusion:** Considering the potential beneficial characteristics of water immersion and the increasing popularity of ATM running, a clearer understanding of the biomechanical alterations is warranted in order to aid practitioners in enhancing outcomes when prescribing ATM running. **Health & Fitness Journal of Canada 2018;11(4):66-79.**

Keywords: Biomechanics; Running; Aquatic Treadmill; Rehabilitation; Water

From ¹ Physical Activity Promotion and Chronic Disease Prevention Unit, University of British Columbia, Vancouver, British Columbia, Canada, Vancouver, BC, Canada V6T1Z3; ²Experimental

Medicine Program, Faculty of Medicine, University of British Columbia, Vancouver, British Columbia, Canada, V5Z 1M9; ³Fortius Sport and Health, Burnaby, British Columbia, Canada, V5B 0A7

*Corresponding Author:

nicholas.held@alumni.ubc.ca

Introduction

Running is a popular form of exercise for recreational and competitive athletes. In the United States alone an estimated 36 million individuals participate in running each year, with 10.5 million running 100 or more days per year (American Sports Data, 2003). Unfortunately, overuse injuries (i.e., stress fractures) are common among runners with rates ranging from 5% to 16% (Matheson et al., 1987) and epidemiological studies have reported that between 19% and 76% of all distance runners experience at least one lower extremity injury per year (Daoud et al., 2012; Van Gent et al., 2007). Systematic reviews on injuries in distance runners have identified high training loads to be a strong risk factor for injury (Van Middlekoop et al., 2008; Yeung and Yeung, 2001). Given the amount of training stress it is common practice to use alternate forms of running, such as deep water and shallow water running, to aid in recovery of lower body injuries in runners (Town and Bradley, 1991). The water provides unique characteristics as there are fluid forces acting on the body during immersion. The buoyancy force

(upward) acts in the opposite direction to the force of gravity, whereas the drag force acts in the opposite direction to the movement of an object (e.g., limb movement) through the water (Masumoto and Mercer, 2008). When walking in the water immersed to the xiphoid process level, the buoyancy force will reduce weight bearing by 71% compared with being on dry land (Harrison et al., 1992). Previous findings have suggested that deep water running, where individuals run in place with a floatation belt or across a pool without touching the ground, is different from land running in terms of lower-extremity muscle recruitment and kinematics (Moening et al., 1993). Shallow water running, running while making ground contact in shallow water without a moving floor, is more similar to land running than deep water running (Reilly et al., 2003; Frangolias and Rhodes, 1996); however, the increased frontal plane resistance of the water produces a different strategy of locomotion compared to land running (Moening et al., 1993; Kato et al., 2001). More recently, there has been an increase in the popularity of aquatic treadmills (ATM). Similar to deep and shallow water running, several studies have investigated the physiological and biomechanical comparisons between ATM and land treadmill running (Silvers et al., 2007; Schaal et al., 2012; Greene et al., 2011; Watson et al., 2012; Rutledge et al., 2007; Porter et al., 2014; Brubaker et al., 2011; Pohl and McNaughton, 2003; Gleim and Nicholas, 1989; Garner et al., 2014; Rife et al., 2010; Silvers et al., 2014; Bressel et al., 2016). It appears that although there are biomechanical alterations during ATM running, ATM running provides a more similar pattern to running on land as

compared to deep water and shallow water running. ATM running eliminates forward locomotion through the water due to the moving floor belt, which mitigates the increased frontal resistance seen in shallow water running. This allows for a more natural gait pattern (Silvers et al., 2007). Considering the increasing popularity of ATM running a clearer understanding of the biomechanical alterations is warranted. Therefore, the purpose of this narrative review was to discuss the kinematic, kinetic, spatiotemporal, and muscle activation differences between ATM and land treadmill running. Our secondary purpose was to examine the possible benefits and limitations of applying an aquatic running intervention as a means for returning to run or sport.

Methods

We conducted a rigorous narrative review of the literature synthesizing the findings from computerized database searches (including MEDLINE, Embase, Cochrane Central Register of Controlled Trials (CENTRAL), Web of Science, SPORTDiscus, and CINAHL), hand searches, and leading texts in the field. Owing to the relatively limited number of studies in the field we opted for a narrative appraisal of the literature.

Findings

Properties of water immersion during exercise

Aquatic exercise is well accepted as a form of conditioning for individuals recovering from injury and/or seeking an effective mode of cross-training (Reilly et al., 2003; Silvers et al., 2014). When considering the biomechanical response to ATM running, there are two primary factors to consider. The first factor is the

buoyancy that an aquatic environment provides (Newman, 1997). It has been reported that based off the depth of submersion, the upward-lifting force of buoyancy markedly unloads the lower extremities as demonstrated by the reduced vertical ground-reaction forces during walking in water (Barela et al., 2006; Nakazawa et al., 1994; Roesler et al., 2006). The second factor to consider is the drag forces imposed when limbs move through water (Newman, 1997; di Prampero, 1986), which increase the resistance to movement, as water is approximately 800 times denser than air (di Prampero, 1986). The magnitude of the drag encountered is proportional to the relative squared limb velocity and frontal surface area of the moving limbs (di Prampero, 1986). Considering the contribution of the upper body to ATM running, this is a large factor to consider when comparing alterations during ATM and land running. It has also been suggested that the transition from walking to running may occur at a lower speed during ATM compared land treadmill locomotion (Kato et al., 2001).

Kinematic differences between land and ATM running

Many kinematic measures are critical for understanding injury risk potential (Daoud et al., 2012) and have been associated with impact peaks and loading rates in studies assessing injury risk in distance running (Bonacci et al., 2013; Chambon et al., 2015; Lieberman et al., 2010; Squadrone et al., 2015). Many have suggested that alterations in gait kinematics in water reflect a strategy to overcome buoyancy and dynamic drag forces in water (Kato et al., 2001; Silvers et al., 2014; Bressel et al., 2016). In addition, it has been suggested that distal

segment kinematics could be more affected in water than proximal kinematics as they display larger radii of rotation about the hip, which produces greater tangential velocities and exponentially greater drag forces (Bressel et al., 2012). Peak ankle plantar flexion, knee flexion, and hip flexion angles have been reported to be greater during ATM compared to land treadmill running (Kato et al., 2001). It has been suggested that during ATM running individuals demonstrate a greater hip joint flexion to move the knee position higher and enable a greater knee joint flexion (Kato et al., 2001). It is possible that these adjustments occur in order to reduce the hydrodynamic resistance of the water and achieve economical locomotion (Kato et al., 2001). In addition, although the maximum range was greater during ATM running speeds of $2.78 \text{ m}\cdot\text{s}^{-1}$ and $3.33 \text{ m}\cdot\text{s}^{-1}$ for thigh angle, knee angle, and ankle angle, the entire range of these joints during ATM running was only greater in the knee joint and was similar in the thigh and ankle joints (Kato et al., 2001). It has been reported that during ATM running at the hip level the ankle joint velocity was lower between 10% and 90% of stride duration and the knee joint velocity was lower between 20-70% and at 100% of stride duration (Kato et al., 2001). Interestingly, Kato et al. (2001) also reported that the velocity of the ankle joint in water at $3.33 \text{ m}\cdot\text{s}^{-1}$ running was almost always held to $1.7 \text{ m}\cdot\text{s}^{-1}$ between 40% to 80% stride duration, which occupied part of the non-support phases. This differed from the knee joint velocity and it was suggested that there might be a physiologically maximum speed of movement in water for each body segment (Kato et al., 2001).

Other kinematic measures that have been associated with reduced impact peaks and loading rates include stride index, overstride angle, and knee contact angle (Bressel et al., 2016). Stride index is defined as the centre of pressure location at foot strike and is often reported as percentage of total foot length (Cavanagh and Lafortune, 1980). In general, lower percentages (i.e., 0-33%) indicate a rear-foot strike pattern while higher percentages (i.e., 34-67% and 68-100%) indicate a mid-foot and forefoot strike pattern, respectively (Bressel et al., 2016). Overstride angle is defined as the absolute angle between the shank and the horizontal plane at foot strike (Bressel et al., 2016). Knee contact angle is defined as the relative knee angle at foot strike where greater values equate to more knee extension (Bressel et al., 2016). It has been reported that strike index during ATM running immersed to the xiphoid process was 61.3% compared to land treadmill running at 42.7%, representing at 18.6% difference between the two environments (Bressel et al., 2016). These percentages suggest that participants appeared to adopt a mid-foot strike in both environments; however, participants contacted more with their forefoot during ATM running. Interestingly, foot strike index was statistically greater during ATM running compared to land treadmill running at all speeds between 2.9 – 3.8 m·s⁻¹, however, there did not appear to be a difference between speeds within each condition. Knee contact angle tended to decrease (greater knee flexion) and overstride angle tended to either increase (less overstride) or not change during ATM compared to land treadmill running (Bressel et al., 2016), possibly suggesting a more compliant strike pattern in the ATM environment (Lieberman, 2014).

One concern with ATM running and the influences of buoyancy could be the increase in vertical displacement of the center of mass. It was reported that there was no difference in the vertical displacement of the hip joint during ATM and land treadmill running at speed of 2.2 – 3.33 m·s⁻¹ (Kato et al., 2001). However, it must be noted that participants were running at waist level water immersion as opposed to the level of the xiphoid process that is more common in the literature. Therefore, it is unclear whether a deeper level of immersion and increased amount of buoyancy would influence the vertical displacement of the hip joint differently.

Kinetic differences between land and ATM running

Measuring kinetic forces (i.e., vertical ground reaction forces) while running on land is very common in the literature as it has been linked to many lower-extremity injuries, such as stress fractures and patellofemoral syndrome (Pohl et al., 2008; Milner et al., 2006; Milner et al., 2010). Vertical ground reaction force represents the force exerted by the ground on the body in contact with it in the vertical axis. During running, the mass of an individual along with the downward force of gravity creates a vertical ground reaction force of 2.5-2.8 times the body weight (Miller, 1990). This amount of repetitive force through the joints can either increase the risk of injury or limit the amount of running an individual can complete following injury as repetitive loading is a key part of the pathophysiology of stress fractures and other injuries (Beck, 1998; Bennell et al., 1999; Jones et al., 2002; Pepper et al., 2006). It has been suggested that various running injuries can be related to the kinetic forces during the

gait cycle including vertical-force loading rates during the early part of stance phase in running (Davis et al., 2004; Milner et al., 2006).

In environmental space studies locomotion under a simulated reduced gravity condition has been investigated to determine kinetic alterations. Davis and colleagues (1996) measured ground reaction forces using a land-based hypogravity simulator and reported lower peak ground reaction forces during locomotion. With increasing depth of water immersion, the upward-lifting force of buoyancy markedly unloads the lower extremities as demonstrated by the reduced vertical ground-reaction forces during walking in water (Barela et al., 2006; Nakazawa et al., 1994; Roesler et al., 2006). Immersion to the anterior superior iliac spine, xiphoid process, and the seventh cervical vertebra reduces limb loading by 57%, 71%, and 85%, respectively during walking (Harrison et al., 1992). Vertical ground reaction forces during shallow water running in hip deep water reached a peak of 100% of body weight and was reduced to 80% in chest deep water (Haupenthal et al., 2010). Similarly, Barela et al. (2006) reported that the rate and magnitude of peak vertical ground reaction forces were about 90% and 23% lower, respectively, during shallow water versus overground walking. Although these studies are very encouraging, the parameters are very different. Participants completed shallow water running on a stationary floor at a self-selected pace and stepped on an underwater force plate. Ground reaction forces positively correlate with running speed and as running speed increases ground reaction forces increase as well (Nilsson and Thorstensson, 1989). As suggested above ATM running allows for

a more comparable gait to land treadmill running by eliminating forward locomotion through the water due to the moving floor belt and mitigating the increased frontal resistance seen in shallow water running (Silvers et al., 2007). Therefore, the kinetic forces reported during shallow water running may be quite different for ATM running. Although the percentages listed above are not specific to running on an ATM, it is likely that ATM running would result in reduced kinetic forces as the effects of buoyancy during water immersion act to counterbalance the force of gravity.

Spatiotemporal differences between land and ATM running

Due to the combined effects of buoyancy and drag forces during ATM running various alterations in spatiotemporal characteristic of running have been noted. For a matched speed and metabolic demand during ATM and land treadmill running, it was found that stride cycle and swing duration were greater during ATM running at xiphoid level immersion. It was also reported that stance duration was similar between environments, however, stance duration was lower and the swing duration was higher during ATM running compared to land running when expressed as a percentage of the stride cycle (Silvers et al., 2014). It should be noted that these characteristics are only qualitative trends based off of means and standard deviations as they were secondary measures that did not include statistical analyses. In agreement, Kato and colleagues (2001) reported that the stance duration was similar and the swing phase was significantly longer during ATM running. It is important to note that Silvers and colleagues (2014) was using

xiphoid level water immersion, whereas Kato and colleagues (2001) used hip level immersion. Therefore, the agreement between these two investigations appears to be evident among various levels of water immersion. It has also commonly been reported that stride frequency is lower during ATM running by 22% to 30% at speeds between 1.95-3.8 m·s⁻¹ (Rutledge et al., 2007; Pohl and McNaughton, 2003; Rife et al., 2010; Kato et al., 2001; Silvers et al., 2014). Interestingly, it has been suggested that the highest stride frequency occurred at 1.67 m·s⁻¹ for both ATM and land treadmill running (Kato et al., 2001). In contrast, Silvers and colleagues (2014) reported increasing stride frequency with increasing speed up to 3.8 m·s⁻¹. It is possible that the transition from walking to running at 1.67 m·s⁻¹ as reported by Kato et al. (2001) may have led to a very short non-support phase duration that is not typical of land running and could have resulted in a higher stride frequency (Newman et al., 1994). In addition, although it can be agreed that stride frequency is lower during ATM running using both hip level and xiphoid level water immersion, the differences in water depth could have influenced the speed at which the highest stride frequency occurs.

Muscle activity differences between land and ATM running

Vast amounts of literature have investigated electromyographic activity during various modes of aquatic exercise including ATM walking (Chevutschi et al., 2007; Masumoto et al., 2008; Masumoto et al., 2004), shallow water walking in a pool (Barela et al., 2006; Kaneda et al., 2007; Kaneda et al., 2008), deep water running (Kaneda et al., 2008), and stationary running in a pool (Alberton et

al., 2011). One theme that has often been reported during aquatic exercise is that normalized muscle activity was consistently reduced in select lower-extremity muscles during ATM locomotion (Masumoto and Mercer, 2008). However, averaged muscle activity during ATM walking has been reported to be greater (Chevutschi et al., 2007) and muscle-activation patterns during shallow water walking were flatter compared with land when submersion depths, treadmill speeds and/or metabolic demands were matched (Barela et al., 2006). In response to external loading during land treadmill running or walking it has been reported that metabolic cost and normalized muscle activation increased (Bourdon et al., 1995; Groppo et al., 2005), whereas vertical unloading decreased metabolic cost (Grabowski and Kram, 2008; Colby et al., 1999; Farley and McMahon, 1992; Teunissen et al., 2007) and muscle activation (Colby et al., 1999; Klarner et al., 2010; Liebenberg et al., 2011). Therefore, considering the upward thrust of buoyancy causes an unloading effect during ATM running it would be expected that changes in muscle activity would occur. Despite the analyses of muscle activation during other forms of aquatic exercise, only one study has investigated the electromyographic response to ATM running (Silvers et al., 2014). These authors examined normalized muscle activation in the lower extremities during ATM and land treadmill running at matched running speeds, as well as the absolute duration and total amount of muscle activation during the running stride cycle. It was reported that the percent of maximal voluntary contraction (%MVC) was 44% and 26.9% lower during ATM running in the vastus

medialis and gastrocnemius, respectively (Silvers et al., 2014). In contrast, the %MVC for the rectus femoris during the swing phase was 48.7% greater during ATM running (Silvers et al., 2014). It was further reported that during ATM running significant increases in %MVC in the rectus femoris and tibialis anterior were seen with increasing running speed. The absolute duration of activation for the vastus medialis, rectus femoris, biceps femoris, and tibialis anterior were 213.1%, 128.1%, 41.3%, and 33% greater respectively during ATM compared with land treadmill running (Silvers et al., 2014). When comparing the total activity of the lower extremity it was reported that the vastus medialis, tibialis anterior, and biceps femoris were 41.9%, 35.7%, and 29.2% greater, respectively, during ATM compared to land treadmill running. In contrast, total activity for the gastrocnemius was 40.1% lower during ATM running (Silvers et al., 2014). It was also reported that total activity of the tibialis anterior increased with increasing speed during ATM running (Silvers et al., 2014). Therefore, it appears that due to the resistance of the water and the influence of buoyancy there are alterations in muscle activation based on running speed and between environments.

Benefits of applying an aquatic running intervention for returning to run

Considering the properties of water, the reduced impact force, and the similar metabolic demands (Silvers et al., 2007) between ATM and land treadmill running, individuals may be able to begin running earlier in the rehabilitation process in an effort to return to running. This not only includes biomechanical aspects of

returning to running, but also allows individuals to incorporate energy system development training specific to running earlier in the rehabilitation process. It would be beneficial for practitioners and participants returning to running if the characteristics of ATM running could positively alter the biomechanical measures during land treadmill running. In this way it would help determine if ATM running is a viable surrogate to land treadmill running (Bressel et al., 2016). Previous investigations have shown that training interventions that include footwear (Willson et al., 2014), stretching (Caplan et al., 2015), and augmented feedback (Agresta and Brown, 2015) have demonstrated the possibility to alter land-running kinematics. In addition, it has been suggested that using real-time visual feedback can reduce the magnitude of peak positive acceleration, impact peak, average loading rate, and instantaneous loading rate when running (Crowell et al., 2010). During a six-week ATM running intervention, acute carry-over changes in strike index and knee contact angles from ATM to land treadmill running has been demonstrated (Bressel et al., 2016). However, no retention was reported in any measures within one week of withdrawing the ATM intervention. Specifically, strike index may have produced an acute carry-over effect to land treadmill running, however acute changes were quickly lost (i.e., within one week) once the ATM running was removed (Bressel et al., 2016). It was suggested that individuals that displayed a rearfoot strike pattern on land in baseline testing shifted towards a more mid-foot strike pattern on land. This pattern would be favourable if the alterations were maintained during land running to reduce impact peaks. It is

possible that a frequent use of ATM running over a longer period or as a larger percentage of total training could potentially increase the retention of a greater strike index and other positive alterations (Bressel et al., 2016). Although the lack of long-term alterations in running mechanics by implementing ATM running may be seen as a limitation, it could also be seen as a benefit assuming that an individual possesses an effective and efficient gait pattern. Based on the current literature, an individual may not negatively influence their gait by including ATM running. This could be beneficial for individuals returning to running after injury, or adding additional miles to training with reduced musculoskeletal load that do not wish to adopt mechanics that are associated with ATM running (Bressel et al., 2016). In order to better understand the influence of ATM running on land running mechanics more research is suggested that includes longer interventions or pairing multiple interventions together (i.e., ATM running and visual feedback).

There are other important considerations when examining the current literature on the acute and chronic effects of ATM running from a biomechanical perspective. First of all, the only study completed used a single-subject design analysis of only three participants that limits the ability to generalize results (Bates, 1996). Secondly, it is important to note that the design of the intervention was to assess the effectiveness of alterations during ATM running to land running mechanics. Therefore, it did not include education on running mechanics that could possibly lead to enhanced retention. It is possible that completing the same intervention with the addition of verbal feedback and

education on the desired adaptations could potentially lead to greater retention in land-based running mechanics. Similarly, including visual feedback via underwater cameras that are common in some ATM (i.e., HydroWorx series ATM) could further enhance retention and create awareness of desired adaptations. However, these are currently speculations as further research is needed.

Studies in microgravity environments have indicated that fast-twitch muscle fibres would be more active than slow-twitch muscle fibres. (Kozlovskaya et al., 1984). Additionally, a microgravity environment simulated by water immersion may alter the recruitment order of motor units facilitating recruitment of larger motor units as force gradation within a muscle follows the size principle (Sugajima et al., 1995). It is possible that facilitation of a recruitment order change and selective activation of fast twitch muscle fibres could influence work efficiency (Kato et al., 2001). During ATM running, recruitment inefficiency may have a negative influence on running mechanics throughout the entirety of an exercise session or possibly lead to adaptation of muscle fibres that would not be beneficial during land running. Conversely, it is possible that completing ATM running as a smaller portion of total running could be used to selectively train fast twitch muscle fibres.

Increases in running performance in long distance runners can be improved by enhancing running economy. Large correlations have been shown between steady state oxygen consumption at various speeds and 10-km time (Conley and Krahenbuhl, 1980). One mechanism for improved running economy appears to be alterations in lower leg musculotendinous stiffness (Spurrs et al.,

2003) leading to an ability of the muscles to store and release elastic energy (Saunders et al., 2004). During running, kinetic energy is stored during forced stretch of a muscle and is partly reused during the subsequent phase of concentric work (Asmussen and Bonde-Petersen, 1974; Simonsen et al., 1985). However, during ATM running it appears that the impact force is reduced which could possibly limit the reuse of stored energy in the series elastic component (Kato et al., 2001). For this reason, it is possible that frequent ATM use could negatively influence running economy. However, it has been suggested that plyometric training can increase running economy (Saunders et al., 2006) and multiple studies suggest that plyometric training while immersed in water may offer similar benefits that are experienced with land based plyometrics (Arazi and Asadi, 2011; Held et al., In Press; Robinson et al., 2004). Therefore, effective programming that includes some aquatic plyometric training could help offset this potential limitation and perhaps further enhance load tolerance and economy when returning to running on land.

Conclusions

Various biomechanical alterations occur during ATM running compared to land treadmill running. These modifications occur due to the effects of buoyancy and drag force during water immersion and alter the kinematics, kinetics, spatiotemporal, and muscle activity measures of running. Currently, it is suggested that chronic biomechanical adaptations of ATM running to land treadmill running do not occur (Bressel et al., 2016). In order to better understand the influence of ATM running on land

running mechanics more research is suggested that includes longer interventions or pairing multiple interventions together (i.e., ATM running and visual feedback). Further information would help practitioners to determine the appropriate implementation of ATM running to enhance the rehabilitation and return to run process, as well as the long-term adaptations to regular use.

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Authors' Qualifications

The authors qualifications are as follows: Nicholas J. Held PhD(c), MHK, BSc (hons), CSCS, R. Kin; Christopher L. MacLean, PhD, MSc; Darren E.R. Warburton PhD, MSc, HFFC CEP.

References

- Agresta, C., and Brown, A. (2015). Gait retraining for injured and healthy runners using augmented feedback: A systematic literature review. *Journal of Orthopaedic and Sports Physical Therapy*, 45(8), 576-584. doi: 10.2519/jospt.2015.5823
- American Sports Data. (2003). *The Superstudy of Sports Participation, Vol 1*. Cortlandt Manor, NY: American Sports Data, Incorporated.
- Alberton, C. L., Cadore, E. L., Pinto, S. S., Tartaruga, M. P., Da Silva, E. M., and Krueel, L. F. M. (2011). Cardiorespiratory, neuromuscular and kinematic responses to stationary running performed in water and on dry land. *European Journal of Applied Physiology*, 111(6), 1157-1166. doi: 10.1007/s00421-010-1747-5
- Arazi, H., and Asadi, A. (2011). The effect of aquatic and land plyometric training on strength, sprint, and balance in young basketball players. *Journal of Human Sport and Exercise*, 6(1), 101-111. doi: 10.4100/jshe.2011.61.12

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- Asmussen, E., and Bonde-Petersen, F. (1974). Storage of elastic energy in skeletal muscles in man. *Acta Physiologica*, 91(3), 385-392. doi: 10.1111/j.1748-1716.1974.tb05693.x
- Barela, A. M., Stolf, S. F., and Duarte, M. (2006). Biomechanical characteristics of adults walking in shallow water and on land. *Journal of Electromyography and Kinesiology*, 16(3), 250-256. doi: 10.1016/j.jelekin.2005.06.013
- Bates, B. T. (1996). Single-subject methodology: an alternative approach. *Medicine and Science in Sports and Exercise*, 28(5), 631-638. doi: 10.1097/00005768-199605000-00016
- Beck, B. R. (1998). Tibial stress injuries. An aetiological review for the purposes of guiding management. *Sports Medicine*, 26(4), 265-279. doi: [10.2165/00007256-199826040-00005](https://doi.org/10.2165/00007256-199826040-00005)
- Bennell, K., Matheson, G., Meeuwisse, W., and Brukner, P. (1999). Risk factors for stress fractures. *Sports Medicine*, 28(2), 91-122. doi: 10.2165/00007256-199928020-00004
- Bonacci, J., Saunders, P. U., Hicks, A., Rantalainen, T., Vicenzino, B. G. T., and Spratford, W. (2013). Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. *British journal of sports medicine*. doi: 10.1136/bjsports-2012-091837
- Bourdin, M., Belli, A., Arzac, L. M., Bosco, C., and Lacour, J. R. (1995). Effect of vertical loading on energy cost and kinematics of running in trained male subjects. *Journal of Applied Physiology*, 79(6), 2078-2085. doi: 10.1152/jappl.1995.79.6.2078
- Bressel, E., Louder, T. J., Hoover, J. P., Roberts, L. C., and Dolny, D. G. (2016). Acute and chronic effects of aquatic treadmill training on land treadmill running kinematics: A cross-over and single-subject design approach. *Journal of Sports Sciences*, 1-9. doi: 10.1080/02640414.2016.1256493
- Bressel, E., Smith, G., Miller, A., and Dolny, D. (2012). Aquatic treadmill walking: quantifying drag force and energy expenditure. *J Sport Rehabil*, 2011-0096. doi: 10.1123/jsr.2012.TR5
- Brubaker, P., Ozemek, C., Gonzalez, A., Wiley, S., and Collins, G. (2011). Cardiorespiratory responses during underwater and land treadmill exercise in college athletes. *Journal of sport rehabilitation*, 20(3), 345. <https://doi.org/10.1123/jsr.20.3.345>
- Butts, N. K., Tucker, M., and Greening, C. (1991). Physiological responses to maximal treadmill and deep water running in men and women. *The American Journal of Sports Medicine*, 19(6), 612-614. doi: [10.1177/036354659101900610](https://doi.org/10.1177/036354659101900610)
- Caplan, N., Rogers, R., Parr, M. K., and Hayes, P. R. (2009). The effect of proprioceptive neuromuscular facilitation and static stretch training on running mechanics. *The Journal of Strength and Conditioning Research*, 23(4), 1175-1180. doi: 10.1519/JSC.0b013e318199d6f6.
- Cavanagh, P. R., and Lafortune, M. A. (1980). Ground reaction forces in distance running. *Journal of biomechanics*, 13(5), 397-406. [https://doi.org/10.1016/0021-9290\(80\)90033-0](https://doi.org/10.1016/0021-9290(80)90033-0)
- Chambon, N., Delattre, N., Guéguen, N., Berton, E., and Rao, G. (2015). Shoe drop has opposite influence on running pattern when running overground or on a treadmill. *European journal of applied physiology*, 115(5), doi: 911-918. 10.1007/s00421-014-3072-x
- Chevutshi, A., Lensel, G., Vaast, D., and Thevenon, A. (2007). An electromyographic study of human gait both in water and on dry ground. *Journal of physiological anthropology and applied human science*, 26(4), 467-473. <https://doi.org/10.2114/jpa2.26.467>
- Colby, S. M., Kirkendall, D. T., and Bruzga, R. F. (1999). Electromyographic analysis and energy expenditure of harness supported treadmill walking: implications for knee rehabilitation. *Gait and posture*, 10(3), 200-205. [https://doi.org/10.1016/S0966-6362\(99\)00035-1](https://doi.org/10.1016/S0966-6362(99)00035-1)
- Conley, D. L., and Krahenbuhl, G. S. (1979). Running economy and distance running performance of highly trained athletes. *Medicine and science in sports and exercise*, 12(5), 357-360. doi: 10.1249/00005768-198012050-00010
- Crowell, H. P., Milner, C. E., Hamill, J., and Davis, I. S. (2010). Reducing impact loading during running with the use of real-time visual feedback. *Journal of Orthopaedic and Sports Physical Therapy*, 40(4), 206-213. doi: 10.2519/jospt.2010.3166.
- Daoud, A. I., Geissler, G. J., Wang, F., Saretsky, J., Daoud, Y. A., and Lieberman, D. E. (2012).

Aquatic Treadmill Running Biomechanics

- Foot strike and injury rates in endurance runners: a retrospective study. *Med Sci Sports Exerc*, 44(7), 1325-34. doi: [10.1249/MSS.0b013e3182465115](https://doi.org/10.1249/MSS.0b013e3182465115)
- Davis, B. L., Cavanagh, P. R., Sommer 3rd, H. J., and Wu, G. (1996). Ground reaction forces during locomotion in simulated microgravity. *Aviation, Space, and Environmental Medicine*, 67(3), 235-242.
- Davis, I., Milner, C. E., & Hamill, J. (2004). Does increased loading during running lead to tibial stress fractures? A prospective study. *Medicine and Science in Sports and Exercise*, 36(5). doi: 10.1249/00005768-200405001-00271
- Di Prampero, P. E. (1986). The energy cost of human locomotion on land and in water. *International journal of sports medicine*, 7(02), 55-72. doi: [10.1055/s-2008-1025736](https://doi.org/10.1055/s-2008-1025736)
- Dowzer, C. N., Reilly, T., Cable, N. T., and Neville, A. (1999). Maximal physiological responses to deep and shallow water running. *Ergonomics*, 42(2), 275-281. doi: [10.1080/001401399185649](https://doi.org/10.1080/001401399185649)
- Farley, C. T., and McMahon, T. A. (1992). Energetics of walking and running: insights from simulated reduced-gravity experiments. *Journal of Applied Physiology*, 73(6), 2709-2712. doi: [10.1152/jappl.1992.73.6.2709](https://doi.org/10.1152/jappl.1992.73.6.2709)
- Frangolias, D. D., and Rhodes, E. C. (1996). Metabolic responses and mechanisms during water immersion running and exercise. *Sports Medicine*, 22(1), 38-53. doi: [10.2165/00007256-199622010-00004](https://doi.org/10.2165/00007256-199622010-00004)
- Garner, R., Wagner, D., Bressel, E., and Dolny, D. G. (2014). Land Versus Water Treadmill Running: Lactate Threshold. *International Journal of Aquatic Research and Education*, 8(1), 3. doi: 10.25035/ijare.08.01.03
- Gleim, G. W., and Nicholas, J. A. (1989). Metabolic costs and heart rate responses to treadmill walking in water at different depths and temperatures. *The American journal of sports medicine*, 17(2), 248-252. doi: [10.1177/036354658901700216](https://doi.org/10.1177/036354658901700216)
- Grabowski, A. M., and Kram, R. (2008). Effects of velocity and weight support on ground reaction forces and metabolic power during running. *Journal of Applied Biomechanics*, 24(3), 288-297. doi: 10.1123/jab.24.3.288
- Greene, N. P., Greene, E. S., Carbuhn, A. F., Green, J. S., and Crouse, S. F. (2011). VO₂ prediction and cardiorespiratory responses during underwater treadmill exercise. *Research quarterly for exercise and sport*, 82(2), 264-273. doi: [10.1080/02701367.2011.10599754](https://doi.org/10.1080/02701367.2011.10599754)
- Grosso, E. R., Eastlack, R. K., Mahar, A., Hargens, A. R., and Pedowitz, R. A. (2005). Simulated hypergravity running increases skeletal and cardiovascular loads. *Medicine and science in sports and exercise*, 37(2), 262-266. doi: 10.1249/01.MSS.0000152732.46744.4F
- Harrison, R. A., Hillman, M., and Bulstrode, S. (1992). Loading of the lower limb when walking partially immersed: implications for clinical practice. *Physiotherapy*, 78(3), 164-166. [https://doi.org/10.1016/S0031-9406\(10\)61377-6](https://doi.org/10.1016/S0031-9406(10)61377-6)
- Hauptenthal, A., Ruschel, C., Hubert, M., de Brito Fontana, H., and Roesler, H. (2010). Loading forces in shallow water running at two levels of immersion. *Journal of rehabilitation medicine*, 42(7), 664-669. doi: 10.2340/16501977-0587
- Held, N.J., Perrotta, A.S., Buschmann, K., Bredin, S.D., and Warburton, D.E.R. (2019). A systematic review of the efficacy of lower body aquatic plyometric training. The development of evidence-based recommendations for practitioners. *Health and Fitness Journal of Canada*. In press.
- Jones, B. H., Thacker, S. B., Gilchrist, J., Kimsey, C. D., and Sosin, D. M. (2002). Prevention of lower extremity stress fractures in athletes and soldiers: a systematic review. *Epidemiologic reviews*, 24(2), 228-247. <https://doi.org/10.1093/epirev/mxf011>
- Kaneda, K., Wakabayashi, H., Sato, D., and Nomura, T. (2007). Lower extremity muscle activity during different types and speeds of underwater movement. *Journal of physiological anthropology and applied human science*, 26(2), 197-200.
- Kaneda, K., Wakabayashi, H., Sato, D., Uekusa, T., and Nomura, T. (2008). Lower extremity muscle activity during deep-water running on self-determined pace. *Journal of Electromyography and Kinesiology*, 18(6), 965-972. <https://doi.org/10.1016/j.jelekin.2007.04.004>

Aquatic Treadmill Running Biomechanics

- Kato, T., Onishi, S., and Kitagawa, K. (2001). Kinematical analysis of underwater walking and running. *Sports Medicine, Training and Rehabilitation*, 10(3), 165-182. doi: <https://doi.org/10.1080/10578310210396>
- Klarner, T., Chan, H. K., Wakeling, J. M., and Lam, T. (2010). Patterns of muscle coordination vary with stride frequency during weight assisted treadmill walking. *Gait and posture*, 31(3), 360-365. doi: [10.1016/j.gaitpost.2010.01.001](https://doi.org/10.1016/j.gaitpost.2010.01.001)
- Kozlovskaya, I. B., Grigoryeva, L. S., and Gevlich, G. I. (1984). Comparative-analysis of the effects of actual and simulated weightlessness on the strength-velocity properties and tone of skeletal-muscles of man. *KOSMICHESKAYA BIOLOGIYA I AVIAKOSMICHESKAYA MEDITSINA*, 18(6), 22-26.
- Liebenberg, J., Scharf, J., Forrest, D., Dufek, J. S., Masumoto, K., and Mercer, J. A. (2011). Determination of muscle activity during running at reduced body weight. *Journal of sports sciences*, 29(2), 207-214. doi: [10.1080/02640414.2010.534806](https://doi.org/10.1080/02640414.2010.534806)
- Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S., Ojiambo Mang'Eni, R., and Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, 463(7280), 531-535. doi: [10.1038/nature08723](https://doi.org/10.1038/nature08723)
- Masumoto, K., and Mercer, J. A. (2008). Biomechanics of human locomotion in water: an electromyographic analysis. *Exercise and sport sciences reviews*, 36(3), 160-169. doi: [10.1097/JES.0b013e31817bfe73](https://doi.org/10.1097/JES.0b013e31817bfe73)
- Masumoto, K., Shono, T., Hotta, N., and Fujishima, K. (2008). Muscle activation, cardiorespiratory response, and rating of perceived exertion in older subjects while walking in water and on dry land. *Journal of Electromyography and Kinesiology*, 18(4), 581-590. doi: [10.1016/j.jelekin.2006.12.009](https://doi.org/10.1016/j.jelekin.2006.12.009)
- Masumoto, K., Takasugi, S. I., Hotta, N., Fujishima, K., and Iwamoto, Y. (2004). Electromyographic analysis of walking in water in healthy humans. *Journal of physiological anthropology and applied human science*, 23(4), 119-127.
- Matheson, G. O., Clement, D. B., McKenzie, D. C., Taunton, J. E., Lloyd-Smith, D. R., and MacIntyre, J. G. (1987). Stress fractures in athletes: a study of 320 cases. *The American Journal of Sports Medicine*, 15(1), 46-58. doi: [10.1177/036354658701500107](https://doi.org/10.1177/036354658701500107)
- Miller, D. I. (1990). Ground reaction forces in distance running. *Biomechanics of distance running*, 203-224.
- Milner, C., Ferber, R., Pollard, C., Hamill, J., and Davis, I. (2006). Biomechanical factors associated with tibial stress fracture in female runners. *Medicine and Science in Sports and Exercise*, 38, 323-328. doi: [10.1249/01.mss.0000183477.75808.92](https://doi.org/10.1249/01.mss.0000183477.75808.92)
- Milner, C., Hamill, J., and Davis, I. (2010). Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture. *Journal of Orthopaedic and Sports Physical Therapy*, 40, 59-66. doi: [10.2519/jospt.2010.3024](https://doi.org/10.2519/jospt.2010.3024)
- Moening, D., Scheidt, A., Shepardson, L., and Davies, G. J. (1993). Biomechanical comparison of water running and treadmill running. *Isokinetics and exercise science*, 3(4), 207-215. doi: [10.3233/IES-1993-3406](https://doi.org/10.3233/IES-1993-3406)
- Nakazawa, K., Yano, H., and Miyashita, M. (1994). Ground reaction forces during walking in water. In *Medicine and science in aquatic sports* (pp. 28-34). Karger Publishers. doi: [10.1159/000423702](https://doi.org/10.1159/000423702)
- Newman, D. J. (1997). Moving through fluids. *Journal of human performance in extreme environments*, 2(1), 106-108.
- Newman, D. J., Alexander, H. L., and Webbon, B. W. (1994). Energetics and mechanics for partial gravity locomotion. *Aviation, space, and environmental medicine*, 65(9), 815-823.
- Nilsson, J., and Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica*, 136(2), 217-227. doi: [10.1111/j.1748-1716.1989.tb08655.x](https://doi.org/10.1111/j.1748-1716.1989.tb08655.x)
- Pepper, M., Akuthota, V., and McCarty, E. C. (2006). The pathophysiology of stress fractures. *Clinics in sports medicine*, 25(1), 1-16. doi: [10.1016/j.csm.2005.08.010](https://doi.org/10.1016/j.csm.2005.08.010)
- Pohl, M., and McNaughton, L. (2003). The physiological responses to running and walking in water at different depths. *Research in Sports Medicine: An International Journal*, 11(2), 63-78. doi: [10.1080/0308354](https://doi.org/10.1080/0308354)

Aquatic Treadmill Running Biomechanics

- Pohl, M., Mullineaux, D., Milner, C., Hamill, J., and Davis, I (2008). Biomechanical predictors of retrospective tibial stress fractures in runners. *Journal of Biomechanics*, 41, 1160-1165. doi: [10.1016/j.jbiomech.2008.02.001](https://doi.org/10.1016/j.jbiomech.2008.02.001)
- Porter, R., Blackwell, S., Smith, G., Wagner, D., Gordin, R., and Dolny, D. G. (2014). Metabolic cost comparison of running on an aquatic treadmill with water jets and land treadmill with incline. *International Journal of Aquatic Research and Education*, 8(1), 4. doi: 10.25035/ijare.08.01.04
- Reilly, T., Dowzer, C. N., and Cable, N. T. (2003). The physiology of deep-water running. *Journal of Sports Science*, 21(12), 959-972. doi: [10.1080/02640410310001641368](https://doi.org/10.1080/02640410310001641368)
- Rife, R. K., Myrer, J. W., Vehrs, P., Feland, J. B., Hunter, I., and Fellingham, G. W. (2010). Water treadmill parameters needed to obtain land treadmill intensities in runners. *Med Sci Sports Exerc*, 42(4), 733-738. doi: 10.1249/MSS.0b013e3181bdc485
- Robinson, L. E., Devor, S. T., Merrick, M. A., and Buckworth, J. (2004). The effects of land vs. aquatic plyometrics on power, torque, velocity, and muscle soreness in women. *The Journal of Strength and Conditioning Research*, 18(1), 84-91. doi: 10.1519/00124278-200402000-00012
- Roesler, H., Hauptenthal, A., Schütz, G. R., and de Souza, P. V. (2006). Dynamometric analysis of the maximum force applied in aquatic human gait at 1.3 m of immersion. *Gait and posture*, 24(4), 412-417. doi: 10.1016/j.gaitpost.2005.09.014
- Rutledge, E., Silvers, W. M., Browder, K., and Dolny, D. (2007). Metabolic-cost comparison between submaximal land and aquatic treadmill exercise. *International Journal of Aquatic Research and Education*, 1(2), 4. doi: 10.25035/ijare.01.02.04
- Saunders, P. U., Pyne, D. B., Telford, R. D., and Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34(7), 465-485. doi: [10.2165/00007256-200434070-00005](https://doi.org/10.2165/00007256-200434070-00005)
- Saunders, P. U., Telford, R. D., Pyne, D. B., Peltola, E. M., Cunningham, R. B., Gore, C. J., and Hawley, J. A. (2006). Short-term plyometric training improves running economy in highly trained middle and long distance runners. *The Journal of Strength and Conditioning Research*, 20(4), 947-954. doi: [10.1519/R-18235.1](https://doi.org/10.1519/R-18235.1)
- Schaal, C. M., Collins, L., and Ashley, C. (2012). Cardiorespiratory responses to underwater treadmill running versus land-based treadmill running. *International Journal of Aquatic Research and Education*, 6(1), 6. doi: 10.1249/01.MSS.0000385952.55426.c7
- Silvers, W. M., Bressel, E., Dickin, D. C., Killgore, G., and Dolny, D. G. (2014). Lower-extremity muscle activity during aquatic and land treadmill running at the same speeds. *Journal of sport rehabilitation*, 23(2), 107-122. doi: 10.1123/JSR.2013-0003
- Silvers, W. M., Rutledge, E. R., and Dolny, D. G. (2007). Peak cardiorespiratory responses during aquatic and land treadmill exercise. *Medicine and science in sports and exercise*, 39(6), 969. doi: 10.1097/mss.0b013e31803bb4ea
- Simonsen, E. B., Thomsen, L., and Klausen, K. (1985). Activity of mono- and biarticular leg muscles during sprint running. *European Journal of Applied Physiology and Occupational Physiology*, 54(5), 524-532. doi: 10.1007/BF00422964
- Spurrs, R. W., Murphy, A. J., and Watsford, M. L. (2003). The effect of plyometric training on distance running performance. *European journal of applied physiology*, 89(1), 1-7. doi: 10.1007/s00421-002-0741-y
- Sugajima, Y., Mitarai, G., Koeda, M., and Moritani, T. (1996). Characteristic changes of motor unit activity in hip joint flexor muscles during voluntary isometric contraction during water immersion. *Journal of Electromyography and Kinesiology*, 6(2), 83-95. doi: 10.1016/1050-6411(95)00020-8
- Squadrone, R., Rodano, R., Hamill, J., and Preatoni, E. (2015). Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. *Journal of sports sciences*, 33(11), 1196-1204. doi: 10.1080/02640414.2014.989534
- 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(24), 4418-4427. doi: [10.1242/jeb.004481](https://doi.org/10.1242/jeb.004481)

Aquatic Treadmill Running Biomechanics

- Town, G. P., and Bradley, S. S. (1991). Maximal metabolic responses of deep and shallow water running in trained runners. *Medicine and Science in Sports and Exercise*, 23(2), 238-241.
- Van Gent, B. R., Siem, D. D., Van Middelkoop, M., Van Os, T. A., Bierma-Zeinstra, S. S., and Koes, B. B. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British journal of sports medicine*. doi: [10.1136/bjism.2006.033548](https://doi.org/10.1136/bjism.2006.033548)
- Van Middelkoop, M., Kolkman, J., Van Ochten, J., Bierma-Zeinstra, S. M. A., and Koes, B. W. (2008). Risk factors for lower extremity injuries among male marathon runners. *Scandinavian journal of medicine and science in sports*, 18(6), 691-697. doi: [10.1111/j.1600-0838.2007.00768.x](https://doi.org/10.1111/j.1600-0838.2007.00768.x)
- Watson, P., Mendonca, C., Lehnhard, R. A., Tu, S., Butterfield, S. A., Bouchard, T., and McKeever, K. H. (2012). The metabolic response to treadmill graded exercise: traditional vs. underwater. *Comparative Exercise Physiology*, 8(1), 11-18. doi: [10.3920/CEP12002](https://doi.org/10.3920/CEP12002)
- Willson, J. D., Bjorhus, J. S., Williams, D. B., Butler, R. J., Porcari, J. P., and Kernozek, T. W. (2014). Short-term changes in running mechanics and foot strike pattern after introduction to minimalistic footwear. *PMandR*, 6(1), 34-43. doi: [10.1016/j.pmrj.2013.08.602](https://doi.org/10.1016/j.pmrj.2013.08.602)
- Yeung, E. W., and Yeung, S. S. (2001). A systematic review of interventions to prevent lower limb soft tissue running injuries. *British Journal of Sports Medicine*, 35(6), 383-389. doi: [10.1136/bjism.35.6.383](https://doi.org/10.1136/bjism.35.6.383).