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Anatomical and Biomechanical Factors Related to Running

Economy in Uphill and Downhill Running

McKenna Taylor

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Anatomical and Biomechanical Factors Related to Running
Economy in Uphill and Downhill Running

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Much is known about running economy while running on level ground surfaces. However, with the dynamic of elevation changes during running, more research is needed to understand how various grades that will favor respective mechanics.

PURPOSE: In this study, we focused on determining whether certain running mechanics and anatomy would predict a runner's oxygen uptake between downhill versus uphill running.

METHODS: Twenty-one experienced runners completed six 5-min running trials (1 shoe x 3 grades x 2 visits) in a Saucony marathon racing shoe model (Type A) on level (3.83 m/s), uphill (+4% grade at 3.35 m/s), and downhill (−4% grade at 4.46 m/s) conditions. These treadmill speeds at each grade were predicted as metabolic equivalents through all grades. We measured submaximal oxygen uptake and carbon dioxide production during the entire trial duration with the last 3 min of each trial being averaged. A best-fitting line was generated through oxygen uptake versus grade to classify whether runners were more economical in uphill or downhill conditions relative to other subjects. The slope of this line indicated whether runners were more economical at uphill or downhill running, where a positive slope represented a more economical uphill versus downhill runner. Various running mechanics were measured using Vicon Nexus and a Bertec treadmill. A linear regression determined any correlations between peak vertical force, stride rate, plantar velocity, and ground time against uphill/downhill running ability.

RESULTS: Peak vertical force was the only factor associated with the slope of oxygen uptake versus grade (running grade ability; $p < 0.01$). The slope of oxygen uptake versus grade averaged 0.076 ± 0.278 ((ml/kg/min) / % grade).

CONCLUSION: Runners that naturally prefer a higher peak vertical force when running on level ground led to a lower running grade ability (lower oxygen uptake during downhill versus uphill running).

Keywords: running economy, uphill and downhill running, running grade ability, Achilles tendon

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Introduction

Running economy is defined as the energy demand for a given speed or pace and can be determined by evaluating an individual's steady-state oxygen consumption at a submaximal running pace (Chen et al., 2007; Saunders et al., 2004). Running economy is related to performance and individuals with a good running economy are those that use less energy and less oxygen while running at a given speed (Breiner et al., 2019; Saunders et al., 2004).

Many different factors can influence a person's running economy. In addition to an individual's training, several inherent factors may include anatomical characteristics and biomechanics (Chen et al., 2007; Kubo et al., 2015). Biomechanical differences could include stride length, ground contact time, stride rate, and velocity. Anatomical characteristics can include tendon elasticity and thickness along with mechanical advantage around the ankle (Raichlen et al., 2011). Running economy also appears to be related to foot and ankle structures, and tendon elasticity is important in the storage and release of energy and is involved in muscle power (Kubo et al., 2015; Raichlen et al., 2011).

Because of the different variables that can affect running economy, it can vary considerably among runners. Studies have shown that running economy differs among modes of exercise as well, and an individual's economy is not the same across various forms (Li et al., 2021). There are different modes of running, including uphill running and downhill running. These two modes have significant physiological and biomechanical differences. Downhill running involves high amounts of eccentric loading and more impact. When running downhill, runners also slow down their cadence and take longer steps (Vincent et al., 2019). Uphill running primarily consists of concentric muscle work and there are greater propulsive forces (Li et al., 2021). Uphill running is also associated with a reduced swing phase and a higher step frequency

(Vernillo et al., 2017). These differences in running modes could affect an individual's cardiorespiratory responses and this could cause a change in running economy (Li et al., 2021).

The purpose of this study was to determine whether a runner's uphill or downhill running economy was related to measurable anatomical/biomechanical characteristics. We looked at the differences in biomechanics and foot and ankle anatomy to see if there is a correlation between those and running economy.

We predicted that individuals with a running grade ability more geared towards uphill running will have a lower peak force, higher stride rate, less time on the ground, a lower mechanical advantage about the ankle, and differences in the Achilles tendon cross-sectional area (CSA) and stiffness. The rationale for this prediction can be attributed to the idea that eccentric muscle force, which would be greater in downhill running, is greater than concentric and those with greater eccentric ability may produce greater forces more naturally (Hody et al., 2019). This can lead to a greater peak force, less time on the ground, and longer strides in individuals who have a greater uphill running ability (Vernillo et al., 2017). Ankle plantar flexion range of motion is greater during uphill running compared to downhill (Neves et al., 2014). This can lead to a lower mechanical advantage and a greater running economy. This connection between ankle range of motion and running economy may lead to the belief that uphill runners will receive a greater benefit from a smaller mechanical advantage (Kovacs et al., 2021; Scholz et al., 2008). The results of this study can help determine what type of individual is better suited for uphill or downhill running.

Methods

Participants

Twenty-two skilled male runners participated in this study. To be classified as a skilled runner, the participants would need to be running at least 40 miles a week. To qualify for this study, subjects needed to be free of any lower extremity injury, and those with current injuries and injuries that occurred within the last month were not included in this study. Subjects needed to be able to run 10 km in under 36:00 min to ensure that they were able to run for the required length of the study. All subjects granted consent before beginning the study.

Protocol

During the first visit to the lab, subjects' height and weight were taken. They were then fitted with a portable metabolic device (Cosmed-K5, Italy) to measure oxygen uptake before running on a treadmill at two different grades: uphill at 4° and downhill at −4°. Both grades were completed on the first day with even-numbered subjects running uphill first and odd-numbered subjects running downhill first. On the second day, even-numbered subjects ran downhill first and odd-numbered subjects ran uphill first. The subjects ran for 15 min total. They warmed up for 3 min, then ran 6 min either uphill or downhill. The treadmill was then changed to the next grade and the participant then ran for another 6 min. Subjects ran at a speed of 3.20 m/s (8:23/mile) for uphill running and 4.46 m/s (6:00/mile) for downhill running. The specific speeds for each grade were based on a formula previously created to predict the running speeds for equal metabolic cost across grades (Robergs et al., 1997). A force-sensing treadmill (Bertec, Columbus, OH) was used to measure force while running at different grades. A side view high-speed camera was used to determine footstrike type. All measurements were taken in the morning between the hours of 7:00 and 8:00 a.m.

Ultrasound Imaging

At the beginning and end of the visit, each participant lay prone on a treatment table. Participants placed their foot against a wall to maintain constant pronation and supination within and between imaging sessions and to create and maintain a 90-degree angle at the ankle joint which was confirmed using a goniometer. Once positioned, participants were marked with a permanent marker on the posterior aspect of the Achilles tendon in a straight line between the apex of the medial and lateral malleolus (Neves et al., 2014). This mark was used to ensure the consistent location of images within trials. All Achilles tendon images were obtained on a 5-s cine loop video. Transverse and longitudinal ultrasound (GE Logic S8, GE Healthcare, Little Chalfont, UK) images of the Achilles tendon were obtained using an ML6-15 probe with the foot against the wall at a 90-degree angle. Elastography of the Achilles tendon was obtained using a 9L ultrasound probe with the foot in a neutral position hanging over the edge of the table. After the application of ultrasound transmission gel, transverse and longitudinal images of the Achilles tendon were taken followed by elastography images.

Data Analysis

During the 6 min of running either uphill or downhill, oxygen uptake was averaged across both days to describe their running economy at that grade and speed. Oxygen uptake was analyzed by plotting O_2 versus time. Peak force, ground time, and stride rate were measured from a force-sensing treadmill (Bertec, Columbus, OH). Force data were collected at 1000 Hz for a 30-s period. Each value for both legs was averaged over 30 strides. Peak force was normalized by body weight. The ankle moment arm was measured before running by using an arch height index measurement system (Jaktool US). Footstrike was measured during running by a high-speed camera and the various forms of footstrike types will be as follows. Heel strike (HS) is defined as when the heel touches the ground first. Midfoot (MS) is when the runner lands with a flat foot. Forefoot (FF) is when the heel never touches the ground and the runner lands on the ball of their foot (Ruder et al., 2019). CSA, thickness, and stiffness of the Achilles tendon were measured manually twice after running using internal software on the GE Logic. To obtain an elastography measurement of the Achilles tendon we utilize the average of three manually drawn circles across two subsequent frames. The circles were spanned to the thickness of the tendon. The interclass correlation coefficient (ICC) for Achilles CSA, length, and stiffness was found to be 0.992, 0.931, and 0.529, respectively. This shows that both the Achilles CSA and length measurements related strongly to each other and stiffness did not.

Statistical Analysis

The slope of an individual's oxygen consumption versus the −4 and 4° grades determined the degree of running grade ability each runner has (Figure 1). Two step-wise multiple linear regressions (one focused on biomechanical factors such as footstrike, peak vertical force, ground time, and stride rate, and one focused on anatomical factors such as ankle moment arm, tendon CSA, and tendon stiffness) determined whether any factors during each grade condition predicted the slope of the line described above.

Results

A significant positive correlation was seen between postrun Achilles CSA and running grade ability. Those individuals who had a smaller postrun CSA were found to have a greater ability for downhill running. Individuals who had a greater postrun Achilles CSA were found to have a greater ability for uphill running (F-statistic = 9.55, $p = 0.006$, adjusted $R^2 = 0.29$; Figure 2).

There was a significant correlation between average ground time and running grade ability. Individuals who presented with a longer average ground time were found to have a greater uphill running ability. Individuals with a shorter average ground time were found to have a greater ability for downhill running (F-statistic = 4.906, $p = 0.039$, adjusted $R^2 = 0.157$; Figure 3).

We did not find any significant relationships between the other anatomical or biomechanical factors and running grade ability including peak vertical force, stride rate, prerun CSA, pre- and postrun Achilles tendon thickness, pre- and postrun Achilles tendon stiffness, foot strike, or Achilles tendon moment arm length.

Discussion

Related to running mechanics, it was anticipated that runners that have a better uphill running grade ability would utilize a lower peak force, higher stride rate, and less time on the ground. Only ground time showed any significant correlation with running grade ability (Figure 3). After measuring various anatomical characteristics of the foot and Achilles tendon, only postrun CSA showed any correlation with running grade ability (Figure 2). Despite the weak correlations, the research indicated two factors of a runner's mechanics and anatomy that are related to uphill and downhill running performance.

Previous studies have shown that the economy of one mode of exercise cannot accurately predict the economy of another mode of exercise and individuals could have different efficacy levels across modes of exercise (Breiner et al., 2019). Various characteristics could contribute to changes in running economy (Barnes & Kilding, 2019). Within this study, we have been able to show that there are factors, both anatomical and biomechanical that can be related to running grade ability. This study shows that individuals may be better suited for uphill or downhill running based on anatomical and biomechanical characteristics.

Individuals with a smaller postrun Achilles CSA may have a greater ability at running downhill and those with a larger postrun Achilles CSA may have a greater ability at running uphill. Individuals with a longer preferred ground time may also have a greater ability for uphill running and individuals with a shorter ground time may have a greater ability for downhill running. This difference may be related to the greater range of motion seen at the ankle joint during uphill running along with the expected larger ground reaction forces seen in faster downhill running which could lead to a greater Achilles tendon load (Gottschall and Kram, 2005; Neves et al., 2014).

Both prerun CSA and pre- and postrun tendon length were approaching significance but were removed from the stepwise linear regression model due to their p-values being greater than 0.05. While there is insufficient research that shows a connection between running grade ability with running mechanics, many believe stride rate should have a connection with running grade ability (Fuller et al., 2016). Our results show a connection with ground time, where lower ground times represented more economical uphill runners.

There are reasons why postrun Achilles CSA showed significance and prerun Achilles CSA did not. The prerun Achilles CSA may have added variability in the measurement. It is unknown whether individuals may have run or engaged in some kind of activity before testing and this could affect their prerun Achilles CSA. This was not controlled for and is a limitation of this study. Future studies should control this possible variable and this may lead to insights regarding prerun Achilles CSA and running grade ability.

The stiffness measurement of the Achilles tendon could also be meaningful to running grade ability, but we were unable to detect anything due to high variability in our subject measurements. As was stated previously, the ICC for Achilles stiffness was 0.529. Slight movements from the measurer or subject can change the values given for stiffness, despite the ultrasound being placed in the same position on the Achilles tendon. The standard deviation of the average prerun stiffness measure was 31.82 kPa and the standard deviation of the average postrun stiffness was 30.88 kPa. These standard deviations show the wide range of values for stiffness that may be more associated with changes in ultrasound scanning than variability among the subjects. The stiffness measurement of the Achilles tendon could be a meaningful factor in running grade ability, but we were unable to obtain an accurate measurement due to possible human and measurement errors. As the field of elastography measurement continues to advance and grow, this could potentially lead to improvements in future elastography studies and stiffness measurements.

The relationship between postrun Achilles CSA and an individual's running grade ability and the relationship between average ground time and running grade ability displayed variation around the regression line with several outliers in both postrun Achilles CSA and ground time. This shows that while postrun Achilles CSA and ground time may be related to running grade ability, other factors cannot be overlooked. There may be other physiological, biomechanical, or anatomical variables that could be influencing an individual's uphill or downhill running ability not measured in the current study. Some of these factors could include muscle fiber type, origin and insertion locations of tendons, muscle stiffness, other anthropometric measures, and preferred joint angles. Future analysis could look into these factors and their relationship with running grade ability. For instance, looking into different aspects of muscle characteristics and their effect on an individual's running grade ability.

Application

The knowledge gained from this study can be applied to changes in training to promote desired improvements in graded running ability. Individuals who have a greater ability for downhill compared with uphill running were correlated with a smaller postrun Achilles CSA and a shorter average ground time. Since these runners were off the ground in less time, there must be some different methods for applying force to the ground. Improving an individual's force production to get them off the ground in a shorter time has the potential to improve their ability for downhill running.

Individuals who had a greater ability for uphill running were associated with a greater postrun Achilles CSA and a longer average ground time. Uphill running involves more concentric muscle activity than downhill (Gottschall & Kram, 2005). Individuals who improve their concentric muscle activation by increasing muscle and tendon CSA could potentially improve their uphill running ability. Future studies that investigate the connection between Achilles tendon properties and running grade will likely find greater value in performing measurements after a warm-up session. Although specialized training geared toward one grade, either uphill or downhill, could potentially have negative effects on the other.

Limitations

We observed a large amount of variability around the regression line. Some of this may be due to the variability seen in runners. Other factors could include errors in the measurement of $\dot{V}O_2$. Measurement errors in $\dot{V}O_2$ were minimized by taking eight minutes of recorded data across two modes of running (uphill and downhill).

Ultrasound scanning and measurement could have the potential to vary across different researchers taking the measurements and scanning. This was minimized by using the same person to do all participants' scanning and measurements. The position in which the participants are placed can also affect the scanning and measurement outcomes of ultrasound. This was minimized by placing the participant prone on a table with their left foot flat up against a wall. Their ankle was placed at a 90-degree angle, which was assessed by a goniometer before each scan.

Conclusion

Certain anatomical and biomechanical differences have the potential to affect an individual's running ability. It was predicted that individuals who had either a better uphill running or downhill running economy would have differences in either peak force, stride rate, ground time, ankle mechanical advantage, and Achilles tendon CSA, thickness, and stiffness. There was no correlation found between the variables peak force, stride rate, ankle mechanical advantage, Achilles length or stiffness, and either uphill or downhill running ability. A smaller postrun Achilles CSA and a shorter average ground time were correlated with a greater downhill running ability. A greater postrun Achilles CSA and longer average ground time was correlated with a greater uphill running ability. This information can be used to make changes in training for specific adaptations in an individual's uphill or downhill running ability. However, there may be other factors that were not measured in this current study that may affect an individual's uphill or downhill running ability.

References

Barnes, K. R., & Kilding, A. E. (2019) A randomized crossover study investigating the running economy of highly-trained male and female distance runners in marathon racing shoes versus track spikes. *Sports Medicine 49*, 331-342, Feb.

Breiner, T. J., Ortiz, A. L. R., & Kram, R. (2019) Level, uphill and downhill running economy values are strongly inter-correlated. *European Journal of Applied Physiology 119*, 257-264, Jan.

Chen, T. C., Nosaka, K., & Tu, J. H. (2007) Changes in running economy following downhill running. *Journal of Sports Sciences 25*, 55-63, Jan 1.

Fuller, J. T., Thewlis, D., Tsiros, M. D., Brown, N. A., & Buckley, J. D. (2016) Effects of a minimalist shoe on running economy and 5-km running performance. *Journal of Sports Sciences 34*, 1740-5, Sep.

Gottschall, J. S., & Kram, R. (2005) Ground reaction forces during downhill and uphill running. *Journal of Biomechanics 38*, 445-52, Mar.

Hody, S., Croisier, J. L., Bury, T., Rogister, B., & Leprince, P. (2019) Eccentric muscle contractions: Risks and benefits. *Frontiers in Physiology 10*, 536.

Kovacs, B., Kobor, I., Sebestyen, O., & Tihanyi, J. (2021) Longer Achilles tendon moment arm results in better running economy. *Physiology International 107*, 527-541, Jan 12.

Kubo, K., Miyazaki, D., Shimoju, S., & Tsunoda, N. (2015) Relationship between elastic properties of tendon structures and performance in long distance runners. *European Journal of Applied Physiology 115*, 1725-1733, Aug.

Li, F., Newton, R. U., Shi, Y., Sutton, D., & Ding, H. Y. (2021) Correlation of eccentric strength, reactive strength, and leg stiffness with running economy in well-trained distance runners. *Journal of Strength and Conditioning Research 35*, 1491-1499, Jun.

Neves, K. A., Johnson, A. W., Hunter, I., & Myrer, J. W. (2014) Does achilles tendon cross sectional area differ after downhill, level and uphill running in trained runners? *Journal of Sports Science & Medicine 13*, 823-8, Dec.

Raichlen, D. A., Armstrong, H., & Lieberman, D. E. (2011) Calcaneus length determines running economy: Implications for endurance running performance in modern humans and Neandertals. *Journal of Human Evolution 60*, 299-308, Mar.

Robergs, R. A., Wagner, D. R., & Skemp, K. M. (1997) Oxygen consumption and energy expenditure of level versus downhill running. *Journal of Sports Medicine and Physical Fitness 37*, 168-74, Sep.

Ruder, M., Jamison, S. T., Tenforde, A., Mulloy, F., & Davis, I. S. (2019) Relationship of foot strike pattern and landing impacts during a marathon. *Medicine & Science in Sports & Exercise 51*, 2073-2079, Oct.

Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004) Factors affecting running economy in trained distance runners. *Sports Medicine 34*, 465-85.

Scholz, M. N., Bobbert, M. F., van Soest, A. J., Clark, J. R., & van Heerden, J. (2008) Running biomechanics: Shorter heels, better economy. *Journal of Experimental Biology 211*, 3266-71, Oct.

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J. B., Samozino, P., Horvais, N., & Millet, G. Y. (2017) Biomechanics and physiology of uphill and downhill running. *Sports Medicine 47*, 615-629, Apr.

Vincent, H. K., Massengill, C., Harris, A., Chen, C., Wasser, J. G., Bruner, M., & Vincent, K. R. (2019) Cadence impact on cardiopulmonary, metabolic and biomechanical loading during downhill running. *Gait & Posture 71*, 186-191, Jun.

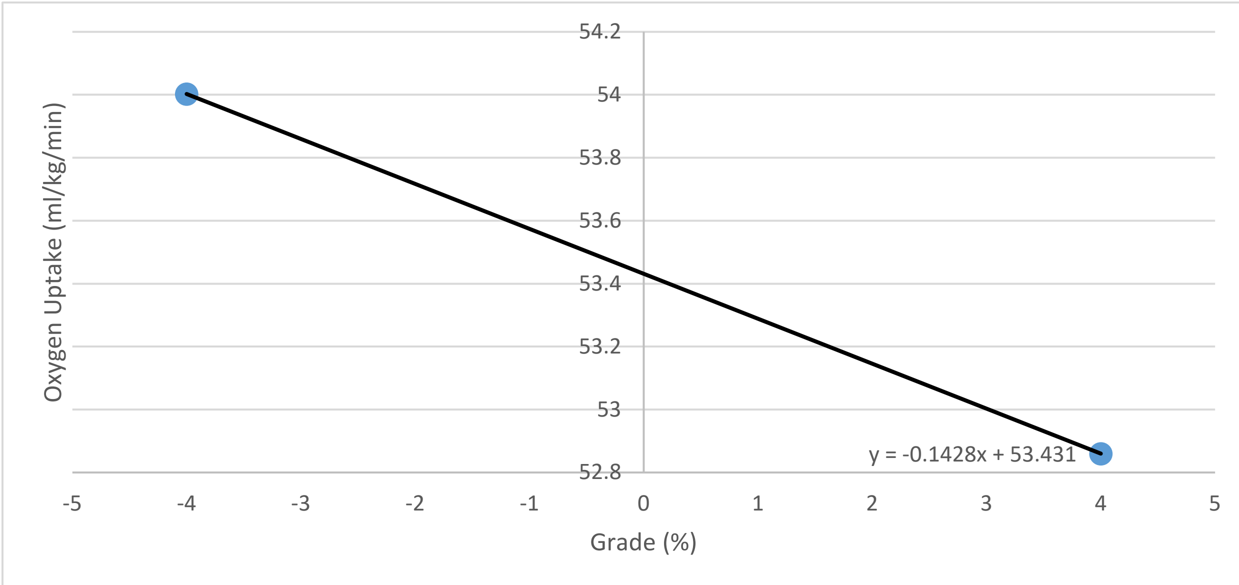

Figure 1: This shows the average running grade ability of an individual who has a greater ability for downhill running

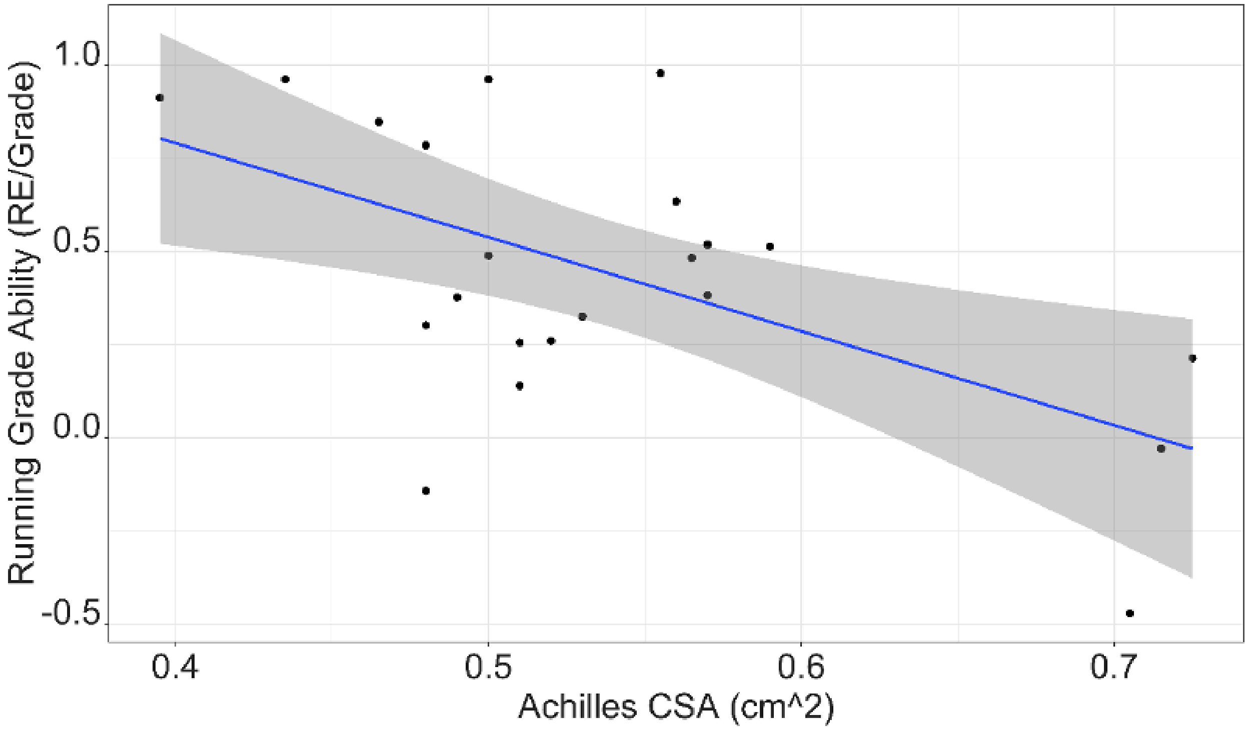

Figure 2: The relationship between postrun Achilles tendon CSA and running grade ability.
Running Grade Ability = 2.53 (postrun CSA) + 1.80

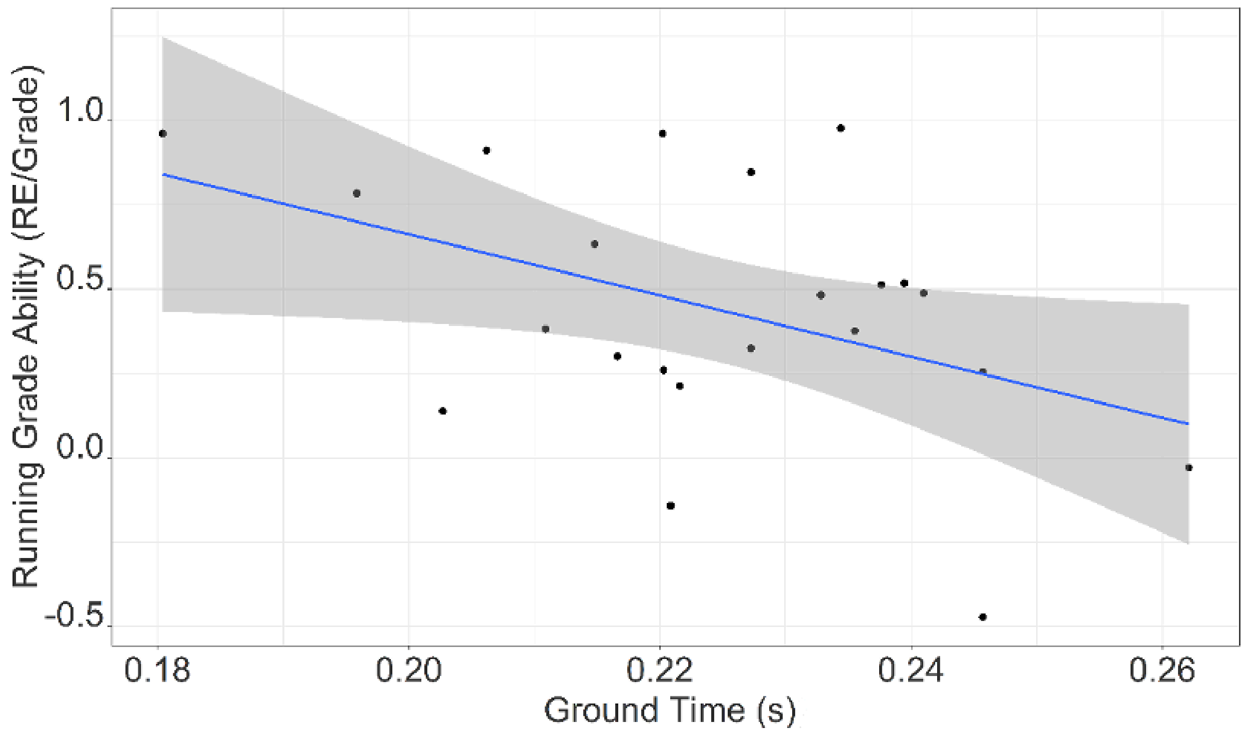

Figure 3: The relationship average ground time and running grade ability.
Running Grade Ability = 9.08 (average ground time) + 2.48