ANALYSING GAIT TRANSITION DYNAMICS IN UPHILL TRAIL RUNNING FROM WEARABLE DEVICES

Raimundo Sanchez[1,2]

1. **Faculty of Engineering and Sciences, Adolfo Ibáñez University, Santiago, Chile.**
2. **School of Health and Rehabilitation Sciences, The University of Queensland, Australia.**

This study investigates gait transition speed in trail running on uphill slopes using wearable devices data. It examines Preferred Transition Speed (PTS) and Heart Rate Optimal Transition Speed (HROTS), noting a decrease in both with increasing slope. This suggests an intuitive adaptation among athletes to lower speeds on steeper inclines, challenging the Iso-Efficient Speed concept and showing gait selection is influenced by more than energy efficiency. The analysis of data from 14 trail runners, aged 22-43 with at least one year of trail running experience, reveals distinct gait patterns characterized by a bimodal distribution in cadence and a unimodal distribution in stride length. These findings suggest that wearable technology not only can aid in analysing athletic performance in natural settings but could also lower the cost of monitoring gait transition parameters for trail runners.

KEYWORDS: Gait transitions, Trail Running, Wearables, Uphill Running.

INTRODUCTION: In trail running, it is commonly observed during uphill sessions that two athletes can maintain the same speed using different gait patterns. Previous studies on pedestrian locomotion have described that as walking speed increases, there is a threshold where a gait transition occurs: subjects switch from walking to running (Kung et al., 2018). This threshold is defined as the Preferred Transition Speed (PTS), with two distinct transition scenarios identified: from walking to running (WRTS), and from running to walking (RWTS) (Hreljac, 1993; Brill & Kram, 2021).

It has been suggested that PTS aims to minimize the energetic cost of transport (CoT) at a given speed, implying that near PTS, it becomes more economical to change gaits (Cavagna & Kaneko, 1977; Minetti, Ardigò & Saibene, 1994; Abe et al., 2019). The CoT increases as the slope steepens because uphill running requires an increase in the body's potential energy, demanding greater net muscular activity than level running (Vernillo et al., 2017). The relationship between CoT and slope has been modelled as linear for walking and quadratic for running (Abe et al., 2019). The intersection of these models allows for the determination of the Energetically Optimal Transition Speed (EOTS), where CoT can be calculated based on VO2 and VCO2 exchange, or the Heart Rate Optimal Transition Speed (HROTS), which is defined using heart rate as a proxy for energy expenditure (Brill & Kram, 2021).

A significant portion of the studies mentioned have been conducted under laboratory conditions since measuring CoT in a laboratory is much more feasible than in the field (Nicot et al., 2021). Wearable devices such as commercially available sports watches are probably the most useful tool for studying athletes outdoors, as most of them allow for the recording of speed, cadence, heart rate, and slope. The use of these devices would enable the study of a wider range of terrains than a laboratory environment. Based on this background, the objective of this work is to identify PTS and HROTS solely from data generated by commercially available wearable devices.

METHODS: Wristwatch data was collected from 14 volunteer trail runners (3 women and 11 men, mean age = 34.64 ± 5.34 years, mean weight = 63.89 ± 8.62 kg, mean height = 170.93 ± 7.70 cm), who shared their training records, resulting in 1559 activity logs encompassing both training and competition data. Participants had at least 1 competition experience during the last year and at least one year of trail running experience. Each participant used a sports watch that measured GPS, heart rate, and cadence, with the tested devices primarily being Garmin Fenix and Garmin Forerunner models. Activities were included if they had a duration of 30 minutes to 2 hours, an elevation gain exceeding 200 meters, and available essential data such as heart rate and cadence. This range was chosen because activities shorter than 30 minutes yielded insufficient data for analysis, while those exceeding 2 hours increased the likelihood of external factors, including fatigue, influencing gait transitioning.

Each recorded activity, sampled at a 1 Hz frequency, provided time, latitude, longitude, elevation, cadence, and heart rate. Secondary calculations from these primary features yielded metrics such as distance covered, elevation gain and loss, horizontal and vertical speed, stride length, and slope inclination. Only uphill segments were analysed. Gait was inferred from stride length and cadence, using Gaussian mixture models for fuzzy clustering to identify two clusters indicative of walking and running. This approach did not account for variables such as flight time, vertical oscillation, or ground reaction forces due to data limitations. A graphical analysis was conducted to explore the distribution of stride length and frequency, complementing bidimensional distribution with marginal distributions for each variable.

PTS was estimated using logistic regression for each slope value, defining gait as a function of speed, with PTS identified where walking and running probabilities equalled. HROTS was determined through two separate regressions for each gait pattern per slope, predicting locomotion cost (measured by heart rate) as a function of speed, following the methodology of Brill & Kram (2021). The intersection of these regression lines indicated the HROTS.

RESULTS: The analysis of the collected data reveals two distinct gait patterns as depicted in Figure 1. This figure highlights a bimodal distribution along the cadence axis, while stride length demonstrates a unimodal distribution.

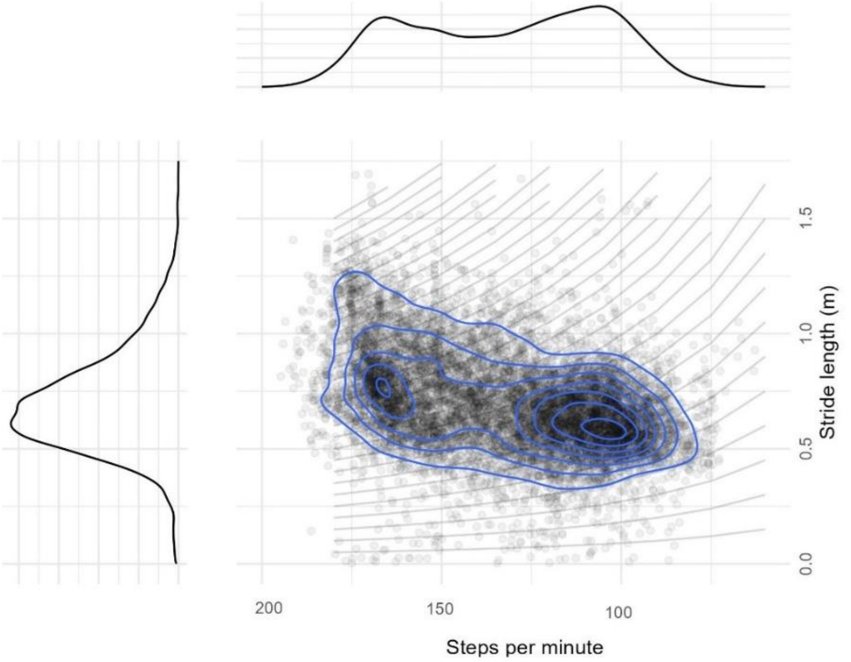

Figure 1: Distribution Analysis of Stride Length and Cadence in Gait Dynamics.

The comprehensive analysis of all computed PTS and HROTS reveals a notable trend, as illustrated in Table 1. This trend manifests as a decreasing pattern for both PTS and HROTS across all participants as inclination increases.

DISCUSSION: This study sheds light on the complex relationship between gait transition and slope in trail running, specifically in uphill scenarios. Our results indicate some degree of overlap or ambiguity in gait patterns around the PTS, suggesting that the transition between walking and running is not always a clear-cut process and may involve a range of intermediate states or individual variations. As the slope increases, both the PTS and the HROTS show a decreasing trend, reflecting an intuitive adaptation of athletes to steeper inclines by transitioning at lower speeds, which is in line with prior findings (Brill & Kram, 2021). There are differences between HROTS and PTS for most inclines, which suggests that gait selection is influenced by a variety of factors, extending beyond the simple minimization of energy expenditure.

Table 1: Comparative Overview of HROTS and PTS across uphill incline. Gait Transition speed data is presented as average and standard deviation.

Incline (deg)	HROTS (m/s)	PTS (m/s)
1	2.01 ± 0.67	1.83 ± 0.69
2	1.97 ± 0.56	1.7 ± 0.58
3	1.85 ± 0.5	1.77 ± 0.51
4	1.87 ± 0.51	1.72 ± 0.45
5	1.78 ± 0.46	1.75 ± 0.41
6	1.64 ± 0.49	1.74 ± 0.42
7	1.54 ± 0.4	1.63 ± 0.29
8	1.35 ± 0.53	1.63 ± 0.28
9	1.38 ± 0.44	1.63 ± 0.42
10	1.17 ± 0.32	1.44 ± 0.27
11	1.14 ± 0.22	1.45 ± 0.25
12	1.05 ± 0.23	1.43 ± 0.24
13	0.87 ± 0.37	1.27 ± 0.23
14	0.73 ± 0.3	1.28 ± 0.26
15	0.82 ± 0.24	1.26 ± 0.3
16	0.79 ± 0.14	1.35 ± 0.43

These results present a challenge to the concept of Iso-Efficient Speed, which posits the adaptation of biomechanical gait parameters to maintain a constant cost of transport (CoT) across varying slopes (Padulo et al., 2012; Milic et al., 2020). The decreasing PTS and HROTS with increasing slope observed in our study suggest that the relationship between biomechanical adaptation and energy efficiency may be more complex than previously understood, particularly in natural, uncontrolled environments.

Interestingly, the study found that the PTS and HROTS values in field conditions do not always align perfectly with laboratory-based models. This discrepancy can be attributed to the dynamic and unpredictable nature of outdoor running, where factors like terrain variability and psychological elements like cognitive load play a significant role (Kung et al., 2018; Vernillo et al., 2017). Uphill running involves working against gravitational acceleration, which has implications for mechanical gait relative to speed and slope. Additionally, muscle fatigue, especially in uphill sections, affects gait transition, as indicated by different levels of mechanical load reported in various muscle groups (Whiting et al., 2020; Abe et al., 2019). The use of poles in uphill sections by some athletes to mitigate localized muscle fatigue (DOMS) is a testament to these biomechanical adaptations.

The application of wearable sports watches in this study has demonstrated their utility in capturing real-world data, enabling the analysis of a wider range of slopes than possible in laboratory settings (Sanchez & Villena, 2020). However, the variability in measurement quality and the lack of control compared to laboratory conditions highlight the need for further refinement in data collection and analysis methods.

This study's approach to understanding gait transitions in trail running is shaped by certain assumptions, one of which is the reliance on stride length and cadence as sole determinants of gait. This method excludes other influential factors like flight time, vertical oscillation, and ground reaction forces, which could offer a more nuanced view of gait mechanics. Additionally, the study only categorizes gait into two distinct patterns – walking and running. This binary classification may not fully capture the variability in gait patterns that could be present in the diverse environment of trail running.

Another limitation is the sample size and the data collection methods. The study involves a relatively small group of 14 trail runners, which might not represent the broader spectrum of trail running enthusiasts. The use of commercially available sports watches, while effective for outdoor data collection, lacks the precision and comprehensiveness of advanced biomechanical tools available in laboratory settings. Moreover, the study does not utilize additional digital devices like skin conductance sensors or inertial measurement units (IMUs), which could provide further insights into physiological and biomechanical aspects of trail running. These limitations highlight areas for potential enhancement in future research.

CONCLUSION: This study highlights the effectiveness of GPS watch data in identifying gait patterns in uphill trail running, revealing its significant potential for cost-effective monitoring of athletic performance in natural environments. The findings demonstrate that wearable device data, despite the inherent complexities of outdoor running, can partially discern the nuances of gait transitions, particularly between walking and running. This could have implications for practitioners in sports biomechanics, coaching, and rehabilitation, as it could offer a more accessible and affordable means to monitor and analyse gait parameters compared to traditional, more expensive laboratory setups. By enabling detailed gait analysis in real-world settings this research paves the way for more widespread and practical applications in enhancing athletic performance, refining training methodologies, and preventing injuries in trail running. Using wearable technology offers a cost-efficient alternative, needing minimal training and a fraction of the financial investment associated with conventional laboratory-based systems. Thus, the study bridges the gap between advanced biomechanical research and its practical, cost-effective application in sports science and athlete development.

Future research should focus on determining the validity of wearable sports watches for measuring variables such as cadence, speed, inclination, and heart rate. Additionally, future studies should compare gait transition parameters between laboratory settings and the real world. Establishing a protocol for gathering high-quality data in real-world conditions is also essential.

REFERENCES

Abe, D., Fukuoka, Y., & Horiuchi, M. (2019). Why do we transition from walking to running? Energy cost and lower leg muscle activity before and after gait transition under body weight support. PeerJ, 7, e8290.

Brill, J. W., & Kram, R. (2021). Does the preferred walk–run transition speed on steep inclines minimize energetic cost, heart rate or neither?. Journal of Experimental Biology, 224(3), jeb233056.

Cavagna, G. A., & Kaneko, M. (1977). Mechanical work and efficiency in level walking and running. The Journal of physiology, 268(2), 467-481.

Hreljac, A. L. A. N. (1993). Preferred and energetically optimal gait transition speeds in human locomotion. Medicine and Science in Sports and Exercise, 25(10), 1158-1162.

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2018). What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. Human movement science, 57, 1-12.

Milic, M., Erceg, M., Palermi, S., Iuliano, E., Borrelli, M., Cè, E., ... & Padulo, J. (2020). Uphill walking at iso-efficiency speeds. Biology of Sport, 37(3), 247-253.

Minetti, A. E., Ardigo, L. P., & Saibene, F. (1994). The transition between walking and running in humans: metabolic and mechanical aspects at different gradients. Acta physiologica scandinavica, 150(3), 315-323.

Padulo, J., Annino, G., Smith, L., Migliaccio, G. M., Camino, R., Tihanyi, J., & D'Ottavio, S. (2012). Uphill running at iso-efficiency speed. International journal of sports medicine, 33(10), 819-823.

Sánchez, R., & Villena, M. (2020). Comparative evaluation of wearable devices for measuring elevation gain in mountain physical activities. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 234(4), 312-319.

Vernillo, G., Millet, G. P., & Millet, G. Y. (2017). Does the running economy really increase after ultra-marathons?. Frontiers in physiology, 8, 783.

Whiting, C. S., Allen, S. P., Brill, J. W., & Kram, R. (2020). Steep (30) uphill walking vs. running: COM movements, stride kinematics, and leg muscle excitations. European Journal of Applied Physiology, 120(10), 2147-2157.