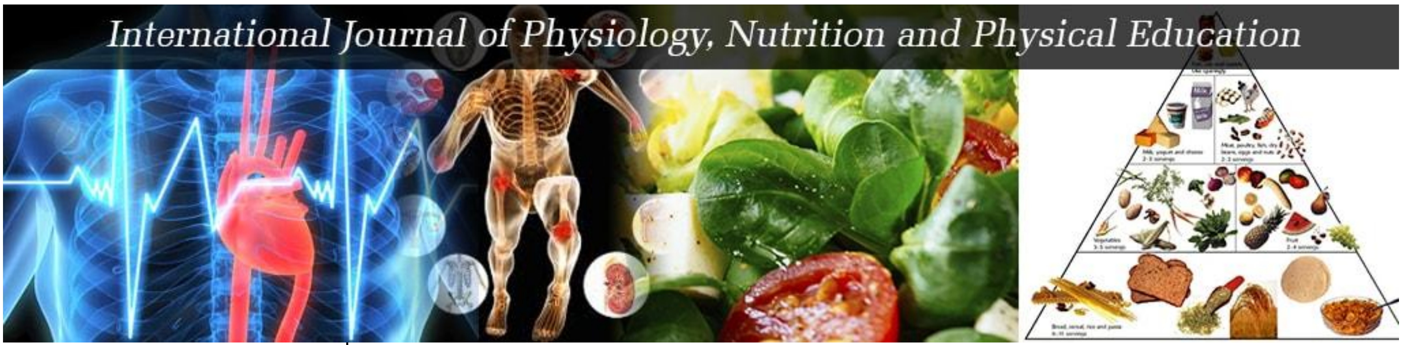

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Comparative biomechanical analysis of running gait across motorized, non-motorized treadmills, and overground surfaces

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Abstract

Purpose: The purpose of this study was to compare the biomechanical gait patterns of recreational runners across four conditions: a motorized treadmill, two arched non-motorized treadmills (Assault Runner and TrueForm), and outdoor overground running. The study also explored how anthropometric characteristics influence running efficiency across these surfaces.
Methods: Twenty recreational runners completed running trials on each surface while their gait was recorded using the Ochy app, a smartphone-based biomechanical analysis tool. Anthropometric data were collected via the Fit3D ProScanner. Efficiency metrics and positional variables were analyzed across conditions, and correlations with body dimensions were assessed.
Results: Outdoor running and the TrueForm treadmill demonstrated the strongest alignment with efficient gait mechanics. The True Form produced the most robust correlations with anthropometric features such as trunk alignment and limb lengths. The Assault Runner showed moderate correlations, while the motorized treadmill had the weakest biomechanical alignment and was most influenced by body size deviations.
Conclusions: Treadmill design significantly impacts running biomechanics. Arched non-motorized treadmills, particularly the TrueForm, more closely replicate overground running and are better suited for performance training and gait analysis. Smartphone-based gait assessment tools offer a practical alternative to laboratory systems, though further validation in larger samples is warranted.

Keywords: Running biomechanics, gait analysis, treadmill comparison

Introduction

Running is one of the most popular forms of physical activity, offering substantial health benefits including improved cardiovascular function, reduced risk of chronic disease, and enhanced psychological well-being (Booth *et al.*, 2012) [2]. However, the repetitive loading inherent in running also contributes to a high incidence of overuse injuries, often linked to altered gait mechanics (van Gent *et al.*, 2007) [9]. As such, the biomechanics of running gait continues to be a focal point in both clinical and performance-related research, particularly in understanding how different running surfaces and equipment impact lower extremity kinematics and kinetics.

Traditional motorized treadmills have long been used in laboratory and clinical settings to standardize running environments for gait analysis (Riley *et al.*, 2008) [7]. Despite their utility, there is evidence suggesting that running gait on a treadmill may differ from overground conditions, potentially limiting the ecological validity of treadmill-based gait assessments (Van Hooren *et al.*, 2020) [10]. More recently, non-motorized treadmills (NMTs), particularly those with curved or arched decks, have gained popularity for their purported ability to mimic outdoor running dynamics more closely (Hollis *et al.*, 2019) [4]. These treadmills require users to propel the belt with their own effort, often resulting in shorter ground contact times, higher stride frequencies, and altered lower limb mechanics when compared to motorized treadmills (Schwarze *et al.*, 2021) [8].

Despite the increased use of curved NMTs in both training and rehabilitation contexts, there remains limited research directly comparing the biomechanical effects of different treadmill types with outdoor running. Previous studies have identified significant differences in joint angles, stride length, and ground reaction forces between treadmill and outdoor conditions (Binnie *et al.*, 2019) [1], but few have systematically examined how multiple treadmill types—especially arched non-motorized treadmills—alter gait mechanics in comparison to each other and to overground running. Understanding these differences is critical for practitioners prescribing treadmill use for performance enhancement, injury prevention, or rehabilitation.

The purpose of this study was to compare the biomechanical gait patterns of recreational runners across four running conditions: a traditional motorized treadmill, two distinct models of arched non-motorized treadmills, and outdoor overground running. This investigation aims to quantify and analyze differences in spatiotemporal parameters, joint kinematics, and segmental coordination across these conditions. The findings will offer valuable insights for clinicians, coaches, and researchers seeking to align treadmill-based training with outdoor running performance and reduce the risk of injury through informed equipment selection.

Methods

Study Design and Purpose

This study employed a within-subjects experimental design to assess running biomechanics and efficiency across four different running surfaces: outdoor overground running, a standard motorized treadmill, an Assault Fitness curved non-motorized treadmill, and a TrueForm curved non-motorized treadmill. The primary objective was to evaluate how different surfaces influence running gait patterns and efficiency and to determine how anthropometric characteristics affect these outcomes. All procedures were approved by the institutional review board, and all participants provided written informed consent prior to participation.

Participants

Twenty recreationally active adults (N = 20) were recruited for this study. Participants were between the ages of 18 and 40 and had no history of lower extremity musculoskeletal injury within the last six months. Inclusion criteria included regular running activity (at least two sessions per week) and familiarity with treadmill use. Exclusion criteria included any diagnosed gait abnormalities, recent surgeries, or balance disorders.

Instrumentation

Ochy Application

The Ochy app (Ochy, Paris, France) was used to assess running biomechanics. The application combines artificial intelligence (AI) with a biomechanical analysis algorithm to evaluate form-based metrics including foot strike, head position, back position, arm swing, front leg cycle, and back leg cycle. The app captures video data and provides quantitative feedback on gait efficiency based on idealized biomechanical models.

Fit3D Scanner

The Fit3D ProScanner (Fit3D Inc., San Mateo, CA) was used to obtain comprehensive anthropometric data for each participant. The scanner provides body composition estimates, segment length and circumference measurements, posture analysis, basal metabolic rate (BMR), and balance assessment. These data were used to identify how individual body characteristics influenced gait performance across surfaces.

Treadmill Descriptions

Standard Treadmill: The motorized treadmill used in this study featured a flat belt surface with adjustable speed settings and a 0% incline. Participants controlled belt speed via console input, and no manual propulsion was required.

Assault Fitness Treadmill: This curved, non-motorized treadmill required self-propulsion and featured a pronounced curve to facilitate belt movement. The curved design allows for high-speed intervals with increased control but introduces mechanical and metabolic differences from flat-surface running.

TrueForm Treadmill: The TrueForm Runner is also a curved non-motorized treadmill. Compared to the Assault Fitness model, it has a subtler curvature and offers higher resistance, requiring greater neuromuscular engagement to sustain running. It is designed to promote a natural gait cycle more akin to outdoor running.

Outdoor Running: A flat, paved surface was used for the outdoor running condition, performed under consistent weather and lighting conditions to reduce variability.

Procedures

Upon arrival, participants completed a Fit3D body scan to assess anthropometric characteristics. Each subject then completed running trials on all four surfaces in a fixed order: (1) Assault Fitness treadmill, (2) TrueForm treadmill, (3) outdoor running, and (4) standard treadmill. This sequence was selected based on pilot testing to minimize fatigue and maximize gait consistency.

During each trial, the Ochy app was used to capture and analyze the subject's running biomechanics. A minimum of 30 seconds of continuous running was recorded for each condition, ensuring consistent speed and form across the different environments. Participants were allowed adequate rest between trials to prevent fatigue-related changes in gait.

Data Analysis

Data from the Ochy application were compiled and evaluated to identify differences in gait efficiency and body mechanics across conditions. Efficiency scores and positional metrics were compared across surfaces, and results were cross-referenced with anthropometric data from the Fit3D scanner to examine how physical traits such as height, limb length, and body composition influenced biomechanical outcomes. Descriptive and inferential statistics were used to determine significant differences and correlations between variables.

Results

Demographics

The provided table (Table 1) presents descriptive statistics for a set of anthropometric and physiological variables. The sample exhibits a range in HEIGHT from 59 to 74 units (mean = 66.6316, SD = 3.93292), and WEIGHT from 98 to 221.7 units (mean = 156.1263, SD = 32.01175). Body density, represented by BDFT_PT, ranged from 6.9 to 38.6 with a mean of 22.9 (SD = 7.98373). Measures of mass, LN_MASS and FT_MASS, showed ranges of 80 to 151.6 (mean = 118.9471, SD = 21.35173) and 10.5 to 70.1 (mean = 37.5118, SD = 17.88232) respectively. Circumference measurements, WAIST_MAX and HIPS_MAX, varied from 27.4 to 40.2 (mean = 33.7474, SD = 4.0496) and 33.9 to 47.3 (mean = 41.0053, SD = 3.25636) respectively. Finally, TOTAL_VOL ranged from 1.5 to 3.6 with a mean of 2.3842 (SD = 0.52203). These descriptive statistics provide foundational insights into the central tendency and variability of the studied population, offering critical context for subsequent inferential analyses or comparative studies in human anthropometry and body composition.

Table 1: Demographic information of study participants

Variable	Minimum	Maximum	Mean	Std. Deviation
HEIGHT (in)	59	74	66.63	3.93
WEIGHT (lbs.)	98	221.7	156.12	32.01
BDFTPT	6.9	38.6	22.91	7.98
LNMASS (lbs.)	80	151.6	118.94	21.35
FTMASS (lbs.)	10.5	70.1	37.51	17.88
WAISTMAX (in)	27.4	40.2	33.74	4.04
HIPSMAX (in)	33.9	47.3	41.01	3.25
TOTALVOL	1.5	3.6	2.38	0.52

Condition

Outside

The results of the biomechanical assessment during outside running conditions revealed several moderate to strong correlations between specific gait parameters and anthropometric or physiological variables. Notably, the OBLC variable demonstrated the highest correlations, particularly with STBLC (r = 0.806) and BDSPRT (r = 0.706), suggesting that lateral body control and sprint balance may be critical components of efficient over ground locomotion. Additional correlations included LNMASS (r = 0.524), SBSI (r = 0.621), and ABSI (r = 0.584), highlighting the influence of body composition and symmetry on gait stability. OFLC showed multiple significant correlations, including FTMASS (r = 0.588), TTL VORT (r = 0.536), and BDFTPT (r = 0.544), emphasizing the impact of foot mass and total body rotational control on stride efficiency. The OAP variable correlated with BDFTPT (r = 0.503), while OHP and OBP each showed moderate associations with BDSPRT (r = 0.474), SBSI (r = 0.486), ABSI (r = 0.49), and FOREARM LEFT (r = 0.492). These findings collectively suggest that both upper and lower body anthropometrics contribute meaningfully to efficient outdoor running mechanics, and that certain physiological traits may enhance biomechanical function during over ground locomotion.

Table 2: Results of the biomechanical assessment during outside running conditions

Category	Variable	Value
OHP	BDSPRT	0.474
OBP	SBSI	0.486
	ABSI	0.491
	FOREARM LEFT	0.492
OAP	BDFTPT	0.503
OFLC	BDFTPT	0.544
	FTMASS	0.588
	TTL VORT	0.536
	HPMVW	0.469
	URISE	0.486
	CENTRAL	0.486
OBLC	STBLC	0.806
	BDSPRT	0.706
	LNMASS	0.524
	SBSI	0.621
	ABSI	0.584

Traditional Treadmill

The provided table presents a collection of anthropometric measurements and their corresponding values, likely obtained during a Traditional Treadmill protocol, as indicated in the first row. The data seems to represent a subset of biomechanical or physiological parameters, with specific measurements listed under the variable column and their associated numerical values in column 3. For instance, STHP is linked to STBP with a value of 0.568. STAP is associated with HEIGHT (0.595), followed by INSEAM LEFT (0.502), INSEAM RIGHT (0.509), OUTSEAM LEFT (0.511), OUTSEAM RIGHT (0.564), and TORSOSAG (0.556). Additionally, STBLC is associated with BDSPRT (0.636) and LNMASS (0.499). These values, ranging from 0.499 to 0.636, likely represent normalized or scaled parameters related to body segment lengths and dimensions during treadmill locomotion. The systematic collection of such data is essential for characterizing individual variations in movement patterns and could contribute to a deeper understanding of gait mechanics, anthropometric influences on performance, or the development of personalized exercise regimens.

Table 3: Correlation analysis between outside running condition and Traditional Treadmill.

Category	Variable	Value
TTHP	BDSPRT	0.474
TTBP	SBSI	0.486
	ABSI	0.49
	FOREARM LEFT	0.492
TTAP	BDFTPT	0.503
TTFLC	BDFTPT	0.544
	FTMASS	0.588
	TTL VORT	0.536
	HPMVW	0.469
	URISE	0.486
	CENTRAL	0.486
TTBLC	STBLC	0.806
	BDSPRT	0.706
	LNMASS	0.524
	SBSI	0.621
	ABSI	0.584

Air Assault Trainer

The correlation analysis of treadmill running on the TrueForm surface revealed several statistically significant relationships between gait parameters and anthropometric measures. Specifically, ATHP demonstrated strong correlations with TORSOSAG (r = 0.665), OUTSEAM RIGHT (r = 0.664), and HEIGHT (r = 0.576), suggesting that trunk sagittal alignment and lower-limb segment length are influential factors in gait performance. Additional correlations included INSEAM RIGHT (r = 0.537), OUTSEAM LEFT (r = 0.531), STFLC (r

= 0.545), and LRV (r = 0.488), highlighting the relevance of leg volume and femoral control in running efficiency. ATEP was most strongly associated with STBP (r = 0.827), indicating a robust connection between posture-based symmetry and treadmill gait. Other significant correlations for ATEP included CROTCHHEIGHT (r = 0.594), OUTSEAM LEFT (r = 0.555), and TORSOSAG (r = 0.567), further reinforcing the importance of lower-body proportions and trunk alignment. ATAP displayed moderate relationships with STFLC (r = 0.611), OAP (r = 0.547), and HEIGHT (r = 0.495), with additional contributions from BDFTPT (r = 0.465) and STAP (r = 0.469). These findings collectively suggest that running on a TrueForm treadmill is influenced by a combination of lower-limb segment lengths, torso alignment, and specific body proportion metrics, all of which may contribute to enhanced biomechanical efficiency and translatability to overground running.

Table 4: Correlation analysis between outside running condition and AirAssault Trainer.

Category	Measure	Value
ATHP	ATAP	0.51
	STFLC	0.545
	HEIGHT	0.576
	LRV	0.488
	CROTCH HEIGHT	0.499
	INSEAM LEFT	0.529
	INSEAM RIGHT	0.537
	OUTSEAM LEFT	0.531
	OUTSEAM RIGHT	0.664
	TORSOSAG	0.665
ATEP	STBP	0.827
	FOREARM LEFT	0.473
	CROTCH HEIGHT	0.594
	OUTSEAM LEFT	0.555
	TORSOSAG	0.567
ATAP	OAP	0.547
	STAP	0.469
	STFLC	0.611
	HEIGHT	0.495
	BDFTPT	0.465

TrueForm Runner

The provided table presents a subset of anthropometric measurements and their corresponding values, likely representing a dataset for biomechanical or physiological analysis within the context of a "TrueForm Runner" study. The data is organized by different "TrueForm" metrics (TFHP, TFBP, TFAP, TFFLC, TFBLC), with each metric associated with several sub-measurements and their respective numerical values. For instance, TFHP includes TFFLC (0.477), ATHP (0.838), OHP (0.468), HEIGHT (0.493), OUTSEAM RIGHT (0.491), and TORSOSAG (0.486). Similarly, TFBP is characterized by ATBP (0.823), STBP (0.836), and STSL (0.468).

TFAP comprises ATAP (0.687), OAP (0.586), STAP (0.571), and STFLC (0.555). TFFLC is detailed by TFHP (0.477), ATFLC (0.656), WRIST LEFT (0.496), and ARV (0.627). Finally, TFBLC includes STHP (0.494), FOREARM RIGHT (0.491), FOREARM LEFT (0.557), and WRIST LEFT (0.495). These measurements, ranging from 0.468 to 0.838, likely represent normalized or scaled values of various body segments and positions, and their systematic collection is crucial for understanding the kinematic and dynamic characteristics associated with the "TrueForm Runner" activity.

Table 5: Correlation analysis between outside running condition and TrueForm Runner treadmill

Category	Measure	Value
TFHP	TFFLC	0.477
	ATHP	0.838
	OHP	0.468
	HEIGHT	0.493
	OUTSEAM RIGHT	0.491
	TORSOSAG	0.486
TFBP	ATBP	0.823
	STBP	0.836
	STSL	0.468
TFAP	ATAP	0.687
	OAP	0.586
	STAP	0.571
	STFLC	0.555
TFFLC	TFHP	0.477
	ATFLC	0.656
	WRIST LEFT	0.496
	ARV	0.627
TFBLC	STHP	0.494
	FOREARM RIGHT	0.491
	FOREARM LEFT	0.557
	WRIST LEFT	0.495

Discussion

The present study examined biomechanical gait patterns across four running conditions—traditional motorized treadmill, two types of arched non-motorized treadmills (AssaultRunner and TrueForm), and outdoor running—using a smartphone application (SPA) to assess anthropometric influences, joint positioning, and overall running form. The results suggest significant differences in biomechanical efficiency depending on the running surface and treadmill design, with implications for training specificity and injury prevention.

Notably, the standard motorized treadmill demonstrated the fewest correlations with efficient running mechanics, and form was most affected by anthropometric traits such as height and weight. This aligns with previous research noting that treadmill running, particularly on motorized units, alters natural gait patterns due to the passive movement of the belt (Van Hooren *et al.*, 2020) [10]. These alterations can affect spatiotemporal parameters such as stride length and ground contact time, potentially reducing transferability to outdoor running. In this study, such interference with natural gait suggests that motorized treadmill use may not be optimal for runners aiming to replicate outdoor biomechanics, especially for individuals whose body dimensions deviate from normative ranges.

In contrast, the AssaultRunner arched non-motorized treadmill showed moderate correlations with both anthropometric measures and body positioning, suggesting a slight improvement in running economy relative to the motorized treadmill. This may be due to the active propulsion required to move the belt, which more closely mimics outdoor running mechanics (Schwarze *et al.*, 2021) [8]. The device appeared to favor runners whose body dimensions align well with the treadmill's design characteristics, indicating that biomechanics and efficiency may be partially equipment-dependent. These findings are relevant to trainers and clinicians selecting treadmills based on individual runner profiles.

Among the three treadmill types evaluated, the TrueForm arched non-motorized treadmill produced the strongest correlations with both physical characteristics and outdoor running gait patterns. These results support previous findings that TrueForm treadmills facilitate more natural gait mechanics and promote neuromuscular engagement similar to overground running (Binnie *et al*., 2019) [1]. The present study adds to this evidence, revealing statistically significant differences in body positioning—specifically alignment and joint angles—that reflect improved running efficiency. Additionally, the SPA-based analysis suggests that subjects displayed postural and movement characteristics within the optimal range while using the TrueForm, which is consistent with efficient form as previously outlined in gait optimization literature (Folland *et al*., 2017) [3].

Importantly, the use of SPAs allowed for accessible and real-time kinematic feedback. While three-dimensional (3D) motion analysis systems remain the gold standard in biomechanics research, they are expensive, require technical expertise, and lack portability (Kanko *et al*., 2021) [5]. In contrast, SPAs are cost-effective, user-friendly, and easily integrated into both clinical and field settings (Kumar *et al*., 2022) [6]. Although SPAs may not provide the depth of a full 3D analysis, the statistically significant differences found across conditions in this study demonstrate their practical utility in assessing running gait and identifying asymmetries or inefficiencies in movement. This supports emerging evidence that SPAs can provide accurate and useful biomechanical insights, especially when resource constraints limit access to more complex systems.

Despite these findings, this study is not without limitations. The small sample size limits the generalizability of the results, and individual variation in footwear, prior experience, and familiarity with treadmill equipment may have influenced running form. Additionally, the use of SPA-based measurements, while practical and informative, may introduce measurement error compared to laboratory-grade motion capture systems. Future research should aim to validate SPA data against 3D motion systems across broader samples and diverse populations to establish normative benchmarks and further improve field-based gait analysis.

Conclusion

This study highlights significant differences in gait biomechanics across various running conditions, with the TrueForm non-motorized treadmill most closely replicating efficient outdoor running mechanics. While motorized treadmills showed the least alignment with efficient form—particularly among individuals with non-average anthropometric characteristics—arched non-motorized treadmills like the AssaultRunner and TrueForm demonstrated meaningful correlations with both body structure and natural gait. The use of smartphone applications proved effective in identifying statistically significant kinematic differences, underscoring their value as accessible tools for clinicians, coaches, and researchers. Given the portability and practicality of SPAs, they offer a promising avenue for expanding real-world gait analysis. However, further research with larger and more diverse samples is warranted to refine treadmill-based training and ensure biomechanical efficiency across different running environments.

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