

FOOTWEAR HISTORIES AND THE DEVELOPING HUMAN FOOT A BIOCULTURAL ANALYSIS OF EXPOSURE TIMING AND LOCOMOTOR FUNCTION

Nguyen Minh Tuan¹ and Tran Thi Lan^{2,*}

¹ Ho Chi Minh City University of Physical Education and Sport, Ho Chi Minh City, Vietnam

² Faculty of Physical Education, Hanoi National University of Education, Hanoi, Vietnam

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Correspondence: tranthilan4@hotmail.com

ABSTRACT

To examine how the timing and social organization of footwear use affect interpretation of foot development and locomotor function. This study examines the childhood associations, timed footwear interventions, immediate mechanical responses and qualitative accounts of shoe use. Comparisons are assessed by allocation, wear duration, anatomical outcome, statistical contrast and dependence between samples. A South African–German childhood comparison included 810 participants; footwear habits coincided with differences in arch characteristics and task performance, while country and activity complicated attribution. In a nine-month randomized school-shoe trial involving 70 children, primary muscle outcomes were not significant. A non-randomized school intervention enrolled 30 children, retained 17 and reused 36 controls; the flexor digitorum brevis group-by-time interaction was significant ($p = 0.026$), whereas other gains were within-group changes. In adults, a six-month transition involving 22 participants increased mean toe-flexion strength by 57.4%, demonstrating continued muscular adaptation. Plantar sensation, arch stiffness and foot-strike behaviour describe different functions. Qualitative studies identify intermittent wear linked to occasions and identity; an Australian school survey locates disagreement about comfort among principals, parents and students. Developmental attribution requires dated records of footwear, wear hours, activity, terrain and the people determining shoe use. Nine recording fields distinguish measured properties from recollection and preserve uncertainty in timing. Adult muscular adaptation prevents current strength from being treated as an immutable record of childhood exposure. The evidence supports interpretation by tissue, task and exposure period rather than a universal ranking of shod and barefoot feet.

Keywords: biological anthropology; footwear exposure; developmental plasticity; school shoes; intrinsic foot muscles; plantar sensation; locomotion.

INTRODUCTION

The developing foot encounters footwear through activities organized by families, schools, occupations and local environments. These arrangements determine which shoe reaches the foot, how long it is worn and the movements performed in it. Footwear therefore has both mechanical properties and a social chronology. Hockey and colleagues' study of shoes across the life course connects retained and remembered footwear with changing identities and bodily experiences (Hockey et al., 2014). Its relevance to kinesiology lies in identifying when and why use changes, while anatomical effects require measurements of the foot itself.

Immediate shoe removal and sustained barefoot activity involve different exposure histories. Removing a supportive shoe changes contact with the ground during a test. Habitual walking without shoes entails repeated loading, abrasion and practice over a longer period. Conversely, a child classified as habitually barefoot may wear shoes at school, during sport or on particular surfaces. The distinction between a testing condition and a history of use is essential when interpreting age-related differences.

Shoe construction also resists a binary classification. The Minimalist Index combines weight, flexibility, heel-to-toe drop, stack height and motion-control or stability features (Esculier et al., 2015). These dimensions describe construction, but do not fully characterize internal fit, toe-box geometry or use on different surfaces. Branthwaite and colleagues' walking investigation in 27 women found that toe-box shape changed forefoot pressure distribution (Branthwaite et al., 2013). Material properties must therefore accompany the categories "shod", "barefoot" and "minimalist" when those categories are used to explain bodily differences.

Reviews have examined habitual barefoot locomotion, children's footwear and gait development, and footwear choice across the life course (Hollander et al., 2017; Wang et al., 2023; D'Août et al., 2025). The question examined here is more specific: what record of footwear use is needed to interpret the timing of an anatomical or functional difference? The analysis separates population associations from footwear effects, immediate mechanical responses from adaptation, and adult characteristics from childhood exposure. It then specifies the dates, measurements and social decisions needed to connect these comparisons to a person's history.

CRITERIA FOR INTERPRETATION

Assessment addressed allocation, participant selection, comparability before exposure, confounding by activity or setting, verification of wear, losses during follow-up and specificity of the measurement. Randomization supports attribution when follow-up and analysis preserve the allocated comparison. Observational adjustment depends on relevant covariates and sufficient overlap between groups. A within-group increase does not establish a treatment effect relative to controls, and a non-significant test does not establish equivalence. Secondary findings require assessment of the number of tests and any adjustment for multiple comparisons.

Interpretation also followed the timescale of each design. Immediate tests identify responses to a shoe-ground interface; longitudinal interventions identify change over their observation period; cross-sectional comparisons identify associations; and mechanical experiments establish function under specified loading. No independent second screening or standardized risk-of-bias instrument was used. These limits restrict the review to a critical examination of the selected comparisons.

FOOT DEVELOPMENT AND FUNCTION ACROSS MEASURED TIMESCALES

CHILDHOOD ANATOMY AND TASK PERFORMANCE

Waseda and colleagues measured 10,155 children aged 6–18 years, describing age-related variation in foot length, navicular height and the ratio between them (Waseda et al., 2014). The sample establishes the importance of age and sex in describing foot growth. Because different children contributed at different ages, its age gradients do not trace individual development or determine the effect of the age at which shoes were first worn.

Hollander and colleagues examined foot morphology in 810 children and adolescents in South Africa and Germany (Hollander et al., 2017). Habitual footwear categories were associated with static arch characteristics, hallux angles and pliability, with differences across age groups. Static arch measurements and the footprint-derived dynamic arch index described different aspects of the foot: plantar contact also depends on soft tissue and loading. Consequently, the measure generating an arch comparison must accompany its anatomical interpretation.

Adjustment for sex, body mass index, ethnicity and physical activity addressed measured differences between participants. Country, terrain, school routines and opportunities for walking nevertheless accompanied the footwear comparison. An association with shoe use under these conditions cannot isolate the contribution of footwear from the wider environment. Repeated observations within the same setting would provide a stronger basis for separating growth from a change in footwear.

Zech and colleagues assessed balance, standing long jump and a 20-m sprint in 385 habitually barefoot and 425 habitually shod participants from the same programme (Zech et al., 2018). Among children aged 6–10 years, the barefoot group performed better in balance and long jump, whereas the shod group sprinted faster. These differences are task-specific; they do not establish a single ordering of motor development. The morphology and performance articles describe related participants rather than two independent confirmations of a footwear effect.

The running investigation also found that rearfoot striking depended on age and testing condition. Younger habitually barefoot children had a higher probability of rearfoot striking in the examined comparison (Hollander et al., 2018). A habitual footwear category therefore cannot determine a fixed contact pattern throughout development. Anatomy, balance, jumping and running describe separate responses within the same multicentre comparison.

SCHOOL-SHOE INTERVENTIONS AND DIFFERENTIAL CHANGE

Quinlan and colleagues randomized 70 children aged 9–12 years to moderately minimalist or standard school shoes for nine months (Quinlan et al., 2022). Primary differences were not significant: partial eta-squared was 0.04 for abductor hallucis size, 0.05 for flexor digitorum brevis size, 0.05 for hallux strength and 0.04 for lesser-toe strength. Posteromedial balance favoured the minimalist group ($p = 0.04$, $\eta_p^2 = 0.07$), as did posterolateral balance ($p = 0.01$, $\eta_p^2 = 0.10$). These variance-based effect sizes do not express force gains or establish clinically important changes in balance. Adjustment for the secondary comparisons cannot be determined from the abstract.

Fong Yan and colleagues enrolled 30 intervention participants and used 36 controls from Quinlan et al. (Fong Yan et al., 2024). Seventeen intervention participants completed the two-term exposure, leaving 13 withdrawals (43.3%). Shoes had a Minimalist Index of 92%; the schedule comprised three school days and 18 hours per week with a gradual transition. Flexor digitorum brevis size showed a significant group-by-time interaction ($F = 5.273$, $p = 0.026$). Increases in abductor hallucis size, toe strength and arch height were changes within the intervention group without significant interactions. Table 1 retains these distinctions.

TABLE 1. ALLOCATION, WEAR SCHEDULE AND ANATOMICAL OR FUNCTIONAL OUTCOMES IN THE TWO SCHOOL-SHOE INVESTIGATIONS. AH: ABDUCTOR HALLUCIS; FDB: FLEXOR DIGITORUM BREVIS; MI: MINIMALIST INDEX.

	Quinlan et al. (2022)	Fong Yan et al. (2024)
Design	Randomized; nine months	Non-randomized; two school terms
Participants	70 randomized, aged 9–12; the abstract does not give analyzed counts for each outcome	30 intervention participants; 17 completed; 36 controls from Quinlan et al.; ages 9–12
Exposure	Moderately minimalist versus standard shoes	MI 92%; three school days/week, 18 h/week; gradual transition
Muscle size	Primary differences non-significant; AH $\eta_p^2 = 0.04$, FDB $\eta_p^2 = 0.05$	FDB group-by-time interaction: $F = 5.273$, $p = 0.026$; AH increased within the intervention group
Toe strength	Primary differences non-significant; hallux $\eta_p^2 = 0.05$, lesser toes $\eta_p^2 = 0.04$	Within-group gains; no significant interaction
Arch and balance	Selected balance directions improved; no equivalent claim about muscle size	Arch-height change within group; no balance improvement
Missing follow-up	Outcome-specific losses are not specified in the abstract	13/30 withdrawals (43.3%)

A change in one group and a non-significant change in another do not establish that the changes differ. That claim requires the direct contrast tested by a group-by-time interaction. The shared controls also prevent the two school investigations from being counted as independent replications. Differences between their findings cannot determine a dose-response relation because allocation, follow-up and comparator timing differ alongside shoe construction. Muscle size and balance must remain separate endpoints when the school evidence is interpreted.

ADULT MUSCULAR ADAPTATION AND ARCH LOADING

Kelly and colleagues demonstrated that plantar intrinsic muscles resist longitudinal arch deformation under external loading (Kelly et al., 2014). Electrical stimulation reduced arch length and increased arch height. This mechanical capacity identifies a route by which repeated muscular activity may affect foot function, while the direction of demand depends on the footwear and task.

Holowka and colleagues recruited 75 minimally shod Rarámuri men and 26 conventionally shod US men (Holowka et al., 2018). The dynamic arch comparison used 30 and 25 participants. Abductor hallucis measurements used 47 and 25, flexor digitorum brevis measurements 54 and 24, and abductor digiti minimi measurements 25 and 20. After body-size adjustment, abductor hallucis and abductor digiti minimi areas differed significantly; flexor digitorum brevis area did not. Unscaled midstance arch stiffness averaged 1774 ± 925 N/cm in the minimally shod group and 1304 ± 477 N/cm in the conventionally shod group, with a significant adjusted comparison ($p = 0.002$). Recruitment totals therefore overstate the sample for any individual outcome. Walking history and environment accompanied the footwear contrast, and muscle area was an anatomical measurement rather than a direct strength test.

Ridge and colleagues randomized 57 runners to minimalist-shoe walking, foot-strengthening exercise or control for eight weeks (Ridge et al., 2019). Both active groups increased muscle size and strength; the control group did not. Running mileage was maintained, while walking in the supplied shoes increased progressively. The comparison identifies

muscular adaptation during an adult programme. It does not reconstruct childhood use or establish persistence after the programme ended.

Curtis and colleagues followed 22 adults transitioning to minimal footwear and 24 controls for six months; 20 experienced users formed a separate comparison (Curtis et al., 2021). Mean toe-flexion strength in the intervention group increased by 57.4% ($p < 0.001$). The percentage refers to change within that group in maximum isometric metatarsophalangeal plantarflexion, rather than a percentage effect adjusted for the controls. The test measures a specified force task; it does not isolate each intrinsic muscle or establish effects on injury, balance or daily mobility. The experienced users are separate participants and cannot supply the subsequent trajectory of those undergoing the transition.

The adult interventions establish continued adaptation in measured muscular properties after the principal period of foot growth. Current strength is consequently an incomplete record of childhood footwear. This finding is specific to muscular function: it does not establish comparable changes in skeletal proportions or determine whether an earlier developmental effect persists in another tissue.

PLANTAR SENSATION AND STRUCTURAL STIFFNESS

Holowka and colleagues found thicker and harder plantar calluses among frequently barefoot participants in Kenya and the United States without the loss of tactile sensitivity expected from greater callus thickness (Holowka et al., 2019). Callus thickness and tactile response were measured properties. They do not supply a count of barefoot childhood hours or establish protective sensation in neuropathy, injury risk or balance performance. Skin thickness, muscle force and skeletal proportions may also change and persist over different durations, which prevents their use as interchangeable evidence of exposure timing.

During treadmill running, Kelly and colleagues measured greater intrinsic muscle activation in shoes alongside reduced longitudinal arch compression (Kelly et al., 2016). The response pertains to the tested shoes and running task. It distinguishes instantaneous electromyographic activity from accumulated training and strength measured after an intervention. The presence of a shoe therefore does not, by itself, determine reduced muscular activity.

Venkadesan and colleagues demonstrated that the transverse tarsal arch contributes more than 40% of longitudinal foot stiffness in their mechanical investigation (Venkadesan et al., 2020). Medial longitudinal arch height alone cannot describe this structural contribution. A footprint category, muscle cross-sectional area and dynamic stiffness measure answer different anatomical questions and require separate interpretation when comparing footwear groups.

RUNNING CONTACT VARIES WITHIN HABITUAL FOOTWEAR GROUPS

Hatala and colleagues studied 38 habitually barefoot Daasanach adults in northern Kenya (Hatala et al., 2013). At self-selected endurance speeds, 96 of 133 trials involved rearfoot strikes (72%); only five trials involved forefoot strikes. Midfoot and forefoot contact became more frequent at higher speeds. The trial distribution describes observed contacts rather than the proportion of people with a permanent strike pattern.

Lieberman and colleagues examined 48 Kalenjin-speaking participants while varying speed, track stiffness and step frequency (Lieberman et al., 2015). Multiple strike types occurred in 72% of habitually barefoot participants and 32% of habitually shod participants. These percentages concern participants exhibiting variation, whereas the Daasanach percentages concern trials. Their denominators differ and cannot be pooled. Both investigations establish the importance of speed, substrate and individual experience when interpreting a contact pattern within a footwear group.

FOOTWEAR PRACTICES AND EXPOSURE CHRONOLOGY

OWNERSHIP, OCCASIONS AND EVERYDAY WEAR

Dilley and colleagues examined high-heeled footwear through focus groups and year-long case studies in the *If the Shoe Fits* project (Dilley et al., 2015). Occasions and life-course circumstances organized intermittent wear and the negotiation of femininity. Hockey and colleagues' account of footwear and life-course identities belongs to the same qualitative project (Hockey et al., 2014). Together, the articles distinguish ownership and attachment from the frequency of wearing a particular pair. They provide related interpretations of one qualitative investigation, rather than independent ethnographic replications.

A retained shoe may prompt detailed recollection of an important event while providing little information about routine walking. Interviews must therefore identify dates, activities and wear duration separately from the significance of the object. Woodward's object-interview methods use material objects to elicit life histories while examining the limits of

verbal descriptions (Woodward, 2016). The method helps identify the circumstances of use; recalled hours and recollected stiffness still require corroboration or an explicit range of uncertainty.

RECORDING DATED FOOTWEAR USE

Table 2 defines nine fields for a footwear history: period, activity, duration, material condition, loading, ground conditions, social decisions, bodily chronology and the evidence supporting each entry. A record belongs to a dated period and activity, allowing school, sport and domestic use to coexist. Independent walking, school entry, work and sport provide interview anchors; these events are not, by themselves, established sensitive periods for a biological response. When dates are uncertain, the earliest and latest plausible ages preserve that uncertainty.

TABLE 2. NINE FIELDS FOR RECORDING FOOTWEAR USE DURING A DATED LIFE PERIOD. THE FIELDS DEFINE OBSERVATIONS AND THEIR UNITS; THEY DO NOT ASSIGN A BIOLOGICAL EXPOSURE SCORE.

Field	Record and units	Verification and uncertainty
Period	Start/end date or age in years and months; transition that defines the interval	Retain earliest/latest plausible dates and the evidence for each boundary.
Use context	School, commute, work, sport, domestic or ceremonial activity; concurrent uses retained	Compare participant account with observation, diary or institutional documentation where available.
Wear duration	Days/week and hours/day for each footwear-activity combination; barefoot intervals recorded separately	Identify measured, diary-based or recalled duration; preserve a range when recall is imprecise.
Material condition	Shoe identity; sole thickness and heel-to-toe drop in mm; internal dimensions; mass in g; flexibility test and units	Distinguish direct measurement, manufacturer specification and qualitative recollection. Preserve test method and shoe condition.
Movement/loading	Steps/day or distance in km/day; carried load in kg where relevant; speed and sport participation	State instrument and observation interval. Avoid assigning current activity measurements to an earlier period.
Ground conditions	Surface, gradient, indoor/outdoor setting, season and relevant changes	Use local descriptions; document how much of the period each condition represents.
Social organization	Person selecting/purchasing shoes; institutional requirements; cost, replacement, comfort and reasons for changing use	Retain stakeholder disagreement and distinguish written requirements from actual compliance.
Bodily sequence	Dated growth measures, symptoms, clinical diagnosis, orthotic use and footwear transitions	Record chronology without attributing symptoms to a shoe solely because they occurred during wear.
Evidence status	Direct observation/document; corroborated recollection; uncorroborated recollection; unavailable information	Record which observation, document or recollection supports each entry, together with conflicting accounts and the reason for choosing one.

For a prospective diary, recorded wear hours during period j and footwear-activity category c are

$$H_{jc} = \sum_{d \in j} h_{dc}, \quad (1)$$

where h_{dc} is the number of hours observed in category c on day d . Categories must occupy non-overlapping clock intervals. A walking hour and a seated school hour remain separate categories even when the same shoes are worn. H_{jc} measures recorded duration, not mechanically equivalent loading across activities. Incomplete diaries require the number of observed days and their coverage of the period to accompany the total.

Retrospective entries retain ranges for uncertain duration; an unknown duration cannot be assigned zero. Historical Minimalist Index values require material measurements or adequate specifications, rather than recollected descriptions alone. Retained shoes, photographs, caregiver accounts and institutional documents can corroborate different fields without determining every field. Agreement between repeated interviews, diaries and direct shoe measurements must be assessed before cumulative historical wear is used to predict an anatomical outcome.

SCHOOL REQUIREMENTS, COMFORT AND CONTINUED PARTICIPATION

Mazzella and colleagues surveyed 80 Australian secondary-school principals, 153 parents and 120 students (Mazzella et al., 2023). Seventy-seven principals indicated that their schools had footwear guidelines. Parents and students assigned

greater importance to comfort in guideline development than principals did. The disagreement identifies distinct roles in determining exposure: institutions regulate, caregivers purchase and students wear the shoes. Self-selection and questionnaire responses limit population estimates, and perceived pain aggravation does not establish clinically verified causation.

The same pair can reach the foot through personal choice, compliance with a requirement or restricted access to alternatives. Caregiver provision, permitted designs, sizes, replacement costs and workplace protection can determine both wear and activity. These circumstances require local observation rather than attribution to an entire country. In Fong Yan et al., some withdrawals concerned appearance, discomfort or tripping (Fong Yan et al., 2024). Acceptability thus influenced continued participation in the intervention, alongside the anatomical responses measured among those completing it.

Between-community comparisons may combine shoe use with walking distance, terrain and economic circumstances. Adjustment can address measured differences but cannot separate exposures that scarcely overlap between sites. When one site contributes nearly all minimally shod participants and another nearly all conventionally shod participants, footwear and site remain closely coupled. Within-community variation and observed transitions provide more direct opportunities to assess footwear separately from its accompanying environment.

Activity also requires a date. Activity before a footwear change may influence shoe selection and confound the comparison. Activity after the change may be affected by comfort or access and may contribute to the response being examined. These possibilities determine which measurements belong in an adjusted analysis; one undated activity value cannot distinguish them.

CULTURAL INTERPRETATION OF BODILY DIFFERENCES

Contemporary minimally shod communities have their own footwear, occupations, terrains and movement practices. They cannot stand for a single prehistoric condition. Holowka and Lieberman's examination of human foot evolution emphasizes the value of experiments on function (Holowka and Lieberman, 2018); current shoe use alone cannot establish ancestry or evolutionary standing. Cultural interpretation concerns how repeated activities and material arrangements reach the body.

Evaluation must likewise specify the task. Greater toe force, greater stiffness, faster sprinting and better balance describe different capacities and can favour different groups. A stronger force test does not establish greater health under every loading demand. Participants' accounts of comfort, mobility and acceptability are required alongside anatomical measurements when a comparison concerns the suitability of footwear for everyday life.

DEVELOPMENTAL INTERPRETATION AND MEASUREMENT REQUIREMENTS

A claim that exposure has a larger effect during one developmental stage requires comparison with a similar exposure at another stage. The central childhood cross-sectional investigations do not make that comparison. Age-related differences may reflect growth, duration, activity or participant selection. Adult muscular adaptation establishes continued responsiveness without determining whether another tissue has an earlier sensitive period. Developmental interpretation must therefore identify the tissue, age interval, activity and duration to which the claim applies.

School transitions offer a setting in which these quantities can be observed together. Measurements before and after a footwear transition, concurrent comparison groups, actual wear records and growth measurements would distinguish pre-existing differences from subsequent change. Observations after withdrawal or later footwear changes would establish persistence. Such observations are requirements for testing developmental timing, rather than outcomes demonstrated by the school investigations examined here.

The anatomical claim should determine the measurement. Muscle adaptation requires standardized force and size assessments; arch mechanics requires loading and dynamic deformation; plantar sensation requires specified stimuli and sites. Interviews and observations identify how school rules, family decisions and occasions organize wear. When measurements are repeated within feet, individuals or schools, the analysis must retain this nesting. Additional outcomes cannot compensate for an unmeasured exposure history or a confounded comparison.

The nine recording fields link a dated shoe–activity combination to the people and circumstances determining it. They also distinguish a measurement from a recollection and an uncertain period from a known duration. Unlike an overall barefoot–shod label, these entries retain simultaneous uses and changes during growth. Their value depends on agreement between repeated accounts and direct observations, completeness across life periods and the extent to which they distinguish exposures relevant to a specified outcome. No reliability coefficient or predictive association has been established for the combined record.

This review is limited by purposive selection, non-exhaustive retrieval and the use of abstracts or indexed passages for several central articles. There was no independently duplicated screening or standardized risk-of-bias assessment. Related participant groups, reused controls, incomplete follow-up, differences between settings and short observation periods restrict causal attribution. The recording fields have not undergone cognitive interviewing or longitudinal validation. Their practical burden and interpretation in different languages and communities require assessment.

Assessment of the nine fields requires repeat interviews for period boundaries, diaries for wear duration and direct measurement of shoe construction. A school transition could then connect dated exposure with repeated tissue measurements, retaining activity before and after the change as separate variables.

CONCLUSION

Footwear reaches the developing foot through dated activities and social decisions. Childhood comparisons associate footwear habits with anatomy and performance, while adult interventions establish continued muscular adaptation. The school evidence supports careful separation of within-group gains from differential change and recognition of shared controls. Plantar sensation, arch mechanics and running contact require their own measurements and timescales. Recording wear hours, material properties, loading, terrain and decision-making would permit a more precise connection between movement anthropology and foot function. Current strength or shoe use alone cannot reconstruct childhood exposure; developmental attribution requires observations linking the exposure period to the measured response.

DECLARATIONS

AUTHOR CONTRIBUTIONS

All authors contributed equally and all authors read and approved the final version of this manuscript.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this study.

DATA AVAILABILITY

All numerical observations are attributed to the cited investigations. This article analyzes literature and contains no newly collected participant measurements. Human participants were not recruited for this review.

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