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The Effects of Footwear Longitudinal Bending Stiffness on the Energetics and Biomechanics of Uphill Running

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A Thesis Presented

By

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ABSTRACT

THE EFFECTS OF FOOTWEAR LONGITUDINAL BENDING STIFFNESS ON THE ENERGETICS AND BIOMECHANICS OF UPHILL RUNNING

SEPTEMBER 2022

JUSTIN ANGELO ORTEGA, B.E. STONY BROOK UNIVERSITY

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There has been a prevalence of long-distance running footwear incorporating carbon-fiber plates within their midsoles, effectively increasing their longitudinal bending stiffness (LBS). This modification of modern racing footwear has occurred concurrently with large improvements in running times (Bermon et al., 2021), putting into question how these footwear components affect performance (Muniz-Pardos et al., 2021). The current literature has investigated this at level running, but with the increasing popularity of trail running, it is of interest to investigate whether the benefits found during level running translate to graded running. Therefore, the overall aim of this study was to investigate the effects of increased footwear midsole longitudinal bending stiffness (i.e. carbon-fiber plates) on running energetics and biomechanics at various inclines. The effects of high LBS (Nike Vaporfly 4% with midsole intact) and low LBS (Nike Vaporfly 4% with mediolateral cuts made at the forefoot of the midsole through the carbon-fiber plate) footwear conditions were compared for running at 0°, 6°, and 12° inclines. Running energetics and biomechanics data were quantified by measuring metabolic rate and lower leg joint mechanics (from motion capture and ground reaction force measurements). Results from this study suggest that increasing longitudinal bending stiffness within the footwear midsoles has limited influence on running energetics (small non-significant improvements of metabolic power at all inclines), but has considerable effects on the biomechanics of the ankle and MTP joints. However, the most important between shoe differences were independent of grade, suggesting that the benefits of modern racing shoe observed for level running can be expected to translate to steep uphill running. Nevertheless, it should be noted that this study was only able to collect and use data for analysis from a limited number of participants (n=7), and therefore is underpowered, so there may be significant differences that go undetected

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CHAPTER 1

INTRODUCTION

Recently, long-distance runners have surged past finish lines in strikingly quick times. World records in the road 5-kilometer, 10-kilometer, half-marathon, and marathon distances have all improved within the last few years. Up in the front, propelling long-distance running performance further, is the Nike Vaporfly shoe. Its innovative design helped Eliud Kipchoge take one small step and a giant leap through the elusive 2-hour marathon barrier (although unofficially, but impressive nonetheless). Such dramatic improvements in performance brought controversy. Many questioned whether the construction of the Vaporfly shoe was fair for competition, especially because of its unique midsole notably comprised with a carbon-fiber plate and high stack height. World Athletics has since deemed the Nike Vaporfly shoe acceptable for competition and numerous other brands have now developed their own variation. Nevertheless, these shoes have only been shown to be effective in flat running courses and level treadmill running (Barnes and Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2022, 2019; Whiting et al., 2021). It is currently unknown if they will be equally effective during steeper uphill running, which is relevant for other running events such as trail running races.

Modern long-distance racing shoes have evolved into a form recognizably divergent from their antecedents. Intuitively, footwear mass would affect long-distance running performance, such that a considerably heavy shoe would *massively* increase the effort to run. Therefore, long-distance running shoes were originally minimal in construction to minimize mass. Since then, new features have been incorporated into the design of running shoes, but more recent innovations have led to footwear midsoles becoming more complex with the incorporation of carbon-fiber plates and fancy (i.e. both highly compliant and resilient) foams, both sculpted with intricate geometries. The successful integration and implementation of these features have led to dramatic improvements in long-distance running performance (Bermon et al., 2021).

The measure of running economy (RE) is a determinant of distance running performance and it is quantified by the rate of oxygen uptake (mLO_2/kg/min) or metabolic power (W/kg), at some defined steady state submaximal running speed (Daniels, 1985). Biomechanical interventions, such as with footwear, can directly influence RE. Footwear features like mass, cushioning, and longitudinal bending stiffness have been shown to have considerable effects.

As mass increases with the addition of cushioning, these two footwear features are inherently related. Studies have suggested that there is ~1% penalty on RE for every 100 grams per shoe (Franz et al., 2012; Frederick et al., 1984; Hoogkamer et al., 2016). Since mass is such a critical consideration for RE, it can be argued that running barefoot may be optimal. Nevertheless, it has been shown that there was no difference in RE when comparing running barefoot and running with sufficiently lightweight footwear (Franz et al., 2012; Tung et al., 2014). Therefore, cushioning has a beneficial effect on RE that counteracts the penalty of ~150 g of mass (Franz et al., 2012).

Ethylene-vinyl acetate (EVA) and Nike Air were initial innovations incorporated into footwear midsole cushioning systems. Early work showed that soft-soled shoes led to improvements in RE (Frederick et al., 1986, 1980). Variations of these midsole technologies have been the primary materials used in current running footwear. Midsole cushioning systems can exhibit properties of compliance and/or resilience. Forms of EVA have mostly demonstrated behavior that was either high in compliance but low in resilience or high in resilience but low in compliance. To overcome this shortcoming, other compounds have recently been explored for constructing midsoles of improved foam properties. Thermoplastic polyurethane (TPU) and polyether block amide (PEBA) as midsole foam materials have demonstrated desirable properties that allow for greater compliance and resilience simultaneously, which further helped enhance the effect of cushioning on RE (Hoogkamer et al., 2018; Worobets et al., 2014).

Manipulating the longitudinal bending stiffness (LBS) of footwear, such as with the incorporation of a carbon-fiber plate, can also influence running economy. Unlike factors such as mass and cushioning, the biomechanical effects of LBS are less understood. Current results have been mixed, likely due to differences in methodologies, however there is a general suggestion that a greater bending stiffness can improve RE, but further increases can diminish such benefits (McLeod et al., 2020; Roy and Stefanyshyn, 2006). Furthermore, the magnitude of RE improvement seems to be dependent on plate placement (insole, embedded, or along the bottom) and shape (flat or curved), mostly modulating metatarsophalangeal and ankle mechanics (Farina et al., 2019).

The topic of carbon-fiber plates in footwear to sufficiently increase bending stiffness to help improve running performance is relatively new. The exact underlying mechanisms of how a carbon-fiber plate influences joint mechanics and RE are currently still being investigated. Nevertheless, to date, all studies that investigated how longitudinal bending stiffness affects running energetics have focused on level running. However, ecological settings and actual running races (except track events) are characterized with inclines and declines of varying degree. Uphill running alters joint mechanics (Khassetarash et al., 2020;

Vernillo et al., 2017). Specifically, there is greater ankle dorsiflexion (Swanson and Caldwell, 2000) and excessive MTP bending (Smith, 1980). Because a carbon-fiber plate in running footwear has shown to mainly impact MTP and ankle mechanics, this project's overall objective is to investigate how increased longitudinal bending stiffness influences RE and MTP and ankle joint mechanics at various inclines.

Aim 1: Characterize and quantify how footwear with increased longitudinal bending stiffness affects the energetics of uphill running at various inclines.

<u>Hypothesis 1:</u> Increased longitudinal bending stiffness will (a) decrease metabolic cost because the benefits at the MTP joint will outweigh the additional costs at the ankle during running at shallower inclines, and (b) increase metabolic cost because the additional costs at the ankle will outweigh the benefits at the MTP joint during running at steeper inclines.

Aim 2: Determine how footwear with increased longitudinal bending stiffness affects uphill running mechanics at various inclines.

<u>Hypothesis 2.1:</u> MTP joint dorsiflexion, moment, and negative work will be decrease.

<u>Hypothesis 2.2:</u> Ankle joint moment, negative work, and positive work will be increased.

Outcomes from this project will expand the understanding of how longitudinal bending stiffness affects overall running performance by investigating its effects with consideration of ecological context (i.e. level vs uphill). Understanding how factors like bending stiffness can affect gait and energetics will provide insight on how to design and develop footwear for improved performance that encourages a more enjoyable experience in whichever activities that athletes, explorers, and outdoor enthusiasts alike are passionate about.

CHAPTER 2

LITERATURE REVIEW

2.1 RUNNING ECONOMY

Distance-running performance can be predicted by maximal O_2 uptake (VO_2max), blood lactate threshold, and running economy (RE) (Joyner, 1991). It has been shown that RE measurements in a laboratory setting can accurately predict distance-running performance related to footwear (Hoogkamer et al., 2016). RE is defined as the rate of oxygen uptake (VO_2, in mLO_2/kg/min) or metabolic power (in W/kg) at a defined steady state submaximal running speed. Since submaximal oxygen uptake and metabolic rate increase with running velocity, an improvement in RE (lower rate of oxygen/metabolic energy consumption at some speed) could improve running performance by allowing runners to increase their pace for the same physiological effort (Daniels, 1985). Nevertheless, there is a curvilinear relationship between oxygen uptake and running velocity, as such recreational runners can achieve larger improvement in running performance from the same % improvements in RE compared to elite marathoners (Kipp et al., 2019).

2.2 FOOTWEAR FEATURES

2.2.1 Mass and Cushioning

Of the various features of running footwear, there is evidence that both the mass and cushioning system of shoes can influence a runner's energy expenditure. In the 1970s, there were innovations in running footwear with the introduction of new materials for shoe midsole cushioning systems. Prior to these innovations, early running shoes only utilized leather and rubber soles. Initial innovations, like ethylene vinyl acetate (EVA) and Nike Air, were incorporated into running footwear and early seminal studies found that footwear mass, and amount or type of cushioning can influence a runner's energy expenditure (Frederick et al., 1986, 1984, 1980). These early findings highlighted the inherent relationship between the mass and cushioning of footwear on running energetics.

As running footwear features became excessive and upon the release of the bestselling book Born to Run (McDougall, 2010), barefoot running became a viable alternative to shod running. Indeed, some studies found barefoot running resulted in improvements in energy expenditure compared to shod running, but significant improvements in RE were only found in studies where comparison was made to shoes that were >300 grams (Figure 2.2.1) (Divert et al., 2008; Flaherty, 1994; Franz et al., 2012; Frederick et al., 1983; Hanson et al., 2011; Pugh, 1970; Squadrone and Gallozzi, 2009). When compared to running in sufficiently lightweight shoes (<150 g), it has been shown there to be no improvement in RE with barefoot running (Franz et al., 2012). Furthermore, consideration of equivalent masses for the footwear conditions resulted in significantly lower metabolic demands (~3-4%) in the shod condition compared to the barefoot condition (Franz et al., 2012). Moreover, to investigate the effects of cushioning independent of shoe mass, Tung et al attached EVA foam panels onto the belt of a treadmill (Tung et al., 2014). They compared unshod running without cushioning, unshod running with 10mm of cushioning, unshod running with 20 mm of cushioning, and shod running in minimal (Nike Free) footwear. For the unshod condition with 10 mm of cushioning, runners on average experienced an improvement in RE compared to the unshod condition without cushioning, and RE was similar between the unshod condition without cushioning and running in lightweight cushioned shoes.

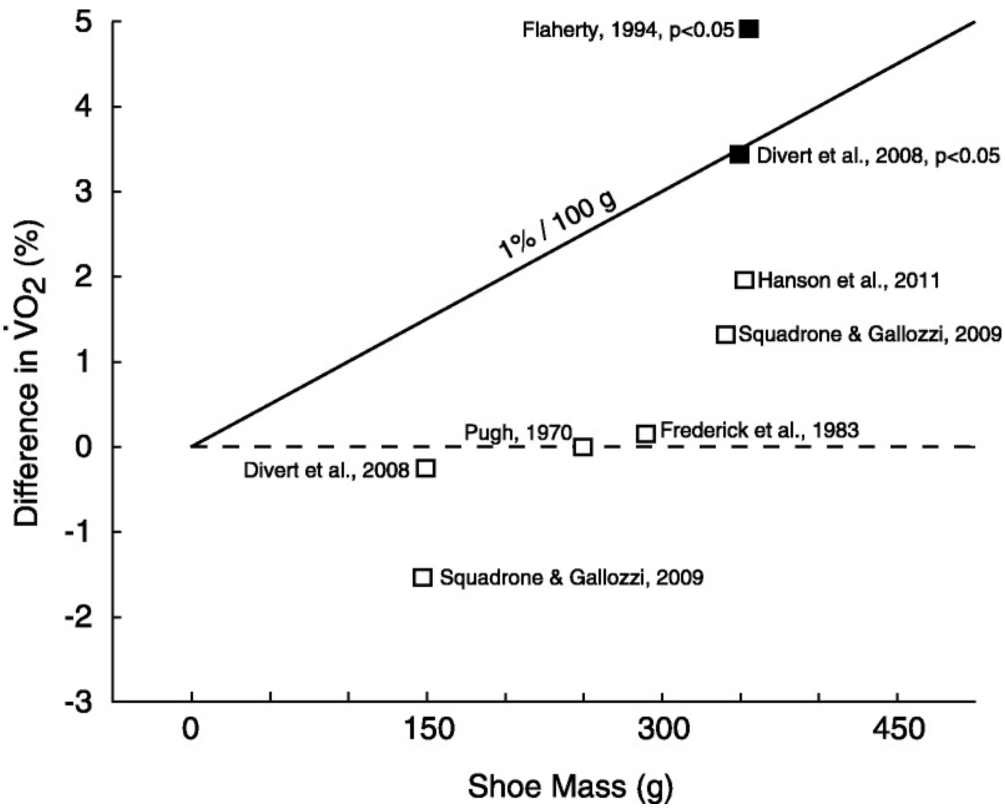

Figure 2.2.1: Percent differences in RE relative to shoe mass between shod running and barefoot running
Significant improvements in RE for barefoot running were only found in studies where comparison was made to shoes that were >300 grams (Figure from Franz et al., 2012).

Currently, EVA proves to still be an effective material for the midsoles of running footwear, as it can be formulated to exhibit either more compliant or resilient properties. Nevertheless, new materials such as thermoplastic polyurethane (TPU) and polyether block amide (PEBA) are being introduced into running footwear cushioning systems. These foam formulations allow for simultaneous improvements in compliance and resilience properties, resulting in significant improvements in RE, demonstrated by adidas footwear with BOOST (TPU) (Worobets et al., 2014) and Nike footwear with ZoomX (PEBA) (Hoogkamer et al., 2018). However, it should be noted that the current studies with footwear utilizing PEBA as a midsole foam material also all incorporate a carbon-fiber plate. Therefore, increasing the longitudinal bending stiffness with a plate may influence the effects of PEBA as a midsole foam, and the relative contributions of the foam and plate are unclear.

2.2.2 Longitudinal Bending Stiffness

In addition to mass and cushioning, longitudinal bending stiffness (LBS) is another footwear feature that has been found to influence RE. The effects of footwear LBS have been outlined in the following manuscript published in Sports Medicine as: Ortega, J.A., Healey, L.A., Swinnen, W., Hoogkamer, W. Energetics and Biomechanics of Running Footwear with Increased Longitudinal Bending Stiffness: A Narrative Review. *Sports Med* 51, 873–894 (2021). https://doi.org/10.1007/s40279-020-01406-5

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REVIEW ARTICLE

Energetics and Biomechanics of Running Footwear with Increased Longitudinal Bending Stiffness: A Narrative Review

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Abstract

In the wake of the quest to break the 2-h marathon barrier, carbon-fiber plates have become commonplace in marathon racing shoes. Despite the controversy surrounding this shoe technology, studies on the effects of increased longitudinal bending stiffness on running economy report mixed results. Here, we provide a comprehensive review of the current litera- ture on midsole bending stiffness and carbon-fiber plates in distance running shoes, focusing on how longitudinal bending stiffness affects running energetics and lower limb mechanics. The current literature reports changes in running economy with increased longitudinal bending stiffness ranging from ~ 3% deterioration to ~ 3% improvement. In some studies, larger improvements have been observed, but often those shoes varied in many aspects, not just longitudinal bending stiffness. Biomechanically, increased longitudinal bending stiffness has the largest impact on metatarsal–phalangeal (MTP) and ankle joint mechanics. Plate location [top loaded (an insole), embedded (in between midsole foam), and bottom loaded (along the bottom of the shoe)] and geometry (flat/curved) affect joint moments and angular velocities at the MTP and ankle joint differently, which partly explains the mixed running economy results. Further research investigating how carbon-fiber plates interact with other footwear features (such as foam and midsole geometry), scaling of those with shoe size, body mass, and strike pattern, and comparing various plate placements is needed to better understand how longitudinal bending stiffness affects running economy.

1 Introduction: It's Gotta Be the Shoes

Since 2018, there has been an unprecedented number of athletes breaking world records in long-distance running races. In 2018, Eluid Kipchoge shaved 78 s off the men's marathon record that stood for four years; in 2019 Brigid Kosgei smashed the 16-year standing women's marathon record and Geoffrey Kamworor broke the men's half marathon world record; and in 2020 Ababel Yeshaneh broke the women's half marathon record. Perhaps most nota- bly, in 2019 Eliud Kipchoge became the first human to run 42.2 km (a marathon) in under two hours. Due to the favorable conditions (e.g., alternating pacers) his effort did not count as an official World Athletics (formerly IAAF) record; however, the feat remains nowhere short of extraordinary.

This recent wave of record breaking has not come without controversy [1–4]. One thing that all of the athletes above have in common, in addition to being exceptionally well trained and talented runners, is the shoes they ran in. The Nike Vaporfly 4% shoe was first released to the public in 2017 with new iterations such as the Nike Vaporfly NEXT% and Nike Alphafly NEXT% released since. An initial study had shown that prototypes of the Vaporfly shoe improved running economy by an average of 4% over other popular marathon shoes (hence their 4% name) [5], leading some to believe the shoes provide an unfair advantage [1, 6, 7]. Subsequent studies on the Vaporfly 4% shoes observed running economy improvements of 2.8–4.2% [8, 9]. The shoes combine a curved carbon-fiber plate with a compliant and resilient midsole foam while still being lightweight [10]. Although soft and compliant foam [11] and lightweight shoes [12–14] are proven factors to improve running economy, for many the full-length curved carbon-fiber plate is the culprit [6].

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Key Points

Increasing longitudinal bending stiffness via the addition of carbon-fiber plates can be an effective way to improve running economy.

The largest improvements in running economy have been observed in shoes with curved or bottom-loaded plates, but this can be confounded due to additional between shoe differences in midsole foam compliance and resilience, and geometry (stack height and toe spring).

Increased longitudinal bending stiffness has the largest impact on metatarsal–phalangeal and ankle joint mechanics.

Much of this controversy stems from the mixed understanding of how the plate works. Upon the release of the shoe, many believed the curved plate was a spring that acted as "a kind of slingshot, or catapult, to propel run- ners forward" [6]. Interestingly, in 2017 the IAAF official rules ambiguously stated shoes "must not give athletes an unfair advantage". This was an amendment from a rule established in 2008 banning "the use of any technical device that incorporates springs". The ambiguity of the 2017 rules and uncertainty surrounding the mechanism of the plate left many people divided on the permissibility of the shoes. However, research has disputed that the plate acts as a pure spring, and in fact, points out that mid- sole foam acts as a spring [10]. World Athletics has since deemed the Vaporfly 4% shoe acceptable for competi- tion and in 2020 the rules were amended to additionally specify the shoe "must not contain more than one rigid plate or blade made from carbon fiber". Carbon-fiber plates are now commonplace with many brands releas- ing performance shoes with embedded plates of different geometries and stiffness.

Despite the controversy and surging popularity, studies into the effect of carbon-fiber plates on running economy have reported mixed results, and the underlying mechanisms are not yet fully understood. Here, we aim to provide a comprehensive review of the current literature on midsole bending stiffness and carbon-fiber plates in distance running shoes, adding to earlier reviews on the effects of running footwear properties on running economy and biomechanics [15, 16] and of footwear lon- gitudinal bending stiffness on athletic injury and perfor- mance [17]. Specifically, we will focus on how midsole bending stiffness affects running energetics and lower limb mechanics.

2 Flex Tests

Currently, there is no standard method of measuring longitudinal bending stiffness of footwear. The most commonly used test is the three-point bending test [18–23], but torsional tests [5] and custom setups [24] have also been used. Even when the same setup is used, displacement ranges, measurement ranges, loading rates, and the number of loading cycles often differ between studies. In Table 1, see Electronic Supplementary Material Appendix S1 Table S1 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table. To allow for comparison, all experimental bending stiffness values reported in N/mm were converted to Nm/rad (see Electronic Supplementary Material Appendix S1 for conversion). It should be noted that force–deformation curves often show nonlinear behavior and hence local linearized stiffness values depend on measurement range. Because measurement range was not standardized between studies, these converted values in Table 1 should not be compared directly between studies that used different measurement ranges.

3 Running Economy

3.1 Running Economy and Distance–Running Performance

Running economy (RE) is an important determinant of distance running performance and can be directly modified through biomechanical interventions [25]. RE is the rate of oxygen uptake ($\dot{V}O_2$, in ml O_2/kg/min) or metabolic power (in W/kg), at a defined steady-state submaximal running speed. As running speed increases, oxygen uptake and metabolic power increase. If a runner can improve their RE, they can increase their speed for the same $\dot{V}O_2$ or metabolic power, and improve their race times [14, 26, 27]. Specifically, Hoogkamer et al. [14] found that for a 1.1% improvement in RE (from adding 100 g extra mass to shoes), distance running performance was slowed by 0.8%. Kipp et al. [27] investigated this disparity and introduced a model accounting for the nonlinear nature of the $\dot{V}O_2$–speed relationship and of air resistance. The implications of this are that recreational athletes (~ 4:30:00 marathon) see larger improvements in performance (1.17% faster) as compared to elite marathoners (~ 2:03:00 marathon, 0.65% faster) for the same 1% improvement in RE [27].

3.2 Longitudinal Bending Stiffness and Running Economy

One way to potentially improve RE is increasing the longitudinal bending stiffness of footwear. Roy and Stefanyshyn

Table 1 Overview of the longitudinal bending stiffness assessment specifics of the articles discussed in the current review

Study	Setup	Displacement range	Measurement range	Loading rate	Cycles	Shoe condition	Experimental bending stiffness	Bending stiffness (Nm/rad)	Shoe mass (g)	Placement
Roy and Stefanyshyn (2006) [18]	3 Point Bending Test	0–7.5 mm	5–6 mm	75 mm/s	20	Adidas Adistar Comp	18 N/mm	7.2	242	Embedded in midsole
						+ CF plate	38 N/mm	15.2	237	
						+ thicker CF plate	45 N/mm	18.0	240	
Willwacher et al. (2013) [31]	3 Point Bending Test	0–7.5 mm	5–6 mm	15 mm/s	5 × 20	Nike Free 3.0	0.65–0.76 N/mm	0.3–0.3	Not reported	Insole
						+ 0.9 mm CF plate	5.29–7.11 N/mm	2.1–2.8		
						+ 3.2 mm CF plate	16.16–17.10 N/mm	6.5–6.8		
Willwacher et al. (2014) [29]	3 Point Bending Test	0–7.5 mm	5–6 mm	15 mm/s	5 × 20	Nike Free 3.0	0.76 ± 0.01 N/mm	0.3	Not reported	Insole
						+ 0.9 mm CF plate	7.11 ± 0.22 N/mm	2.8		
						+ 3.2 mm CF plate	16.16 ± 0.20 N/mm	6.5		
Madden et al. (2016) [19]	3 Point Bending Test	0–7.5 mm	5–6 mm	75 mm/s	20	Adidas PT	8.1 N/mm	3.2	135	Within outsole, forefoot and midfoot
						Adidas PT + CF stiffening plates	23.1 N/mm	9.2	162	
Takahashi et al. (2016) [49]	3 Point Bending Test	5–10 mm	5–10 mm	15 mm/s	20	Barefoot	–	–	Not controlled	Insole
						New Balance 1400	14.8 ± 0.5 N/mm	5.9		
						+ 0.8 mm CF plate	22.5 ± 0.5 N/mm			
						+ 1.6 mm CF plate	28.7 ± 0.8 N/mm	11.5 9.0		
						+ 3.2 mm CF plate	65.6 ± 2.9 N/mm			
Willwacher et al. (2016) [32]	3 Point Bending Test	0–7.5 mm	5–6 mm	15 mm/s	5 × 20	Brooks Pure Connect	1.44 ± 0.03 N/mm	0.6 26.2	Control	Insole
						+ Plastic plate	13.92 ± 0.08 N/mm	5.6		
						+ Fiberglass plate	21.82 ± 0.21 N/mm	8.7	+ < 60	
Oh and Park (2017) [20]	3 Point Bending Test	0–0.5 rad	0–0.5 rad	8.3 mm/s	Not reported	Reebok ZQUICK	1.5 Nm/rad	1.5	Control	Insole
						+ 0.8 mm CF plate	10.0 Nm/rad	10.0		
						+ 1.2 mm CF plate	24.5 Nm/rad	24.5	+ 23 + 12	
						+ 1.5 mm CF plate	32.1 Nm/rad	32.1		
						+ 1.8 mm CF plate	42.1 Nm/rad	42.1	+ 38 + 28	
						+ 2.0 mm CF plate	56.6 Nm/rad	56.6		
						(*n* = 1)			+ 52	
Flores et al. (2019) [21]	3 Point Bending Test	7.5 mm	5–6 mm	15 mm/s	Not reported	Kalenji PU PT	15.4 ± 1.0 N/mm	6.2	369	Underneath insole, forefoot & midfoot
						Kalenji EVA PT	19.2 ± 1.0 N/mm	7.7	368	
						Kalenji PU PT + 0.9 mm CF plate	38.0 ± 1.8 N/mm	15.2	370	
						Kalenji EVA PT + 0.9 mm CF plate	43.2 ± 2.0 N/mm	17.3	367	

Table 1 (continued)

Study	Setup	Displacement range	Measurement range	Loading rate	Cycles	Shoe condition	Experimental bending stiffness	Bending stiffness (Nm/rad)	Shoe mass (g)	Placement
Hoogkamer et al. (2019) [10]	Rotational axis machine test	30°	27°	24°/s	20	Adidas Adizero Adios Boost 2 Nike Zoom Streak 6 Nike Vaporfly PT (curved CF plate)	7.0 Nm/rad 9.4 Nm/rad 18.5 Nm/rad	7.0 9.4 18.5	250 250 250	Embedded in midsole
Cigoja et al. (2019) [30]	3 Point Bending Test	15 mm	80–90% of the loading curve	10 mm/s	10	Nike Free 5.0 + CF plate	1.2 N/mm 11.9 N/mm	1.9 19.0	226 289	Above insole
Day and Hahn (2019) [24]	Custom set up	Not reported	Not reported	Not reported	3	Epic React Flyknit + 3 mm Nylon 11 plate + 2 × 3 mm Nylon plate	5.9 Nm/rad 10.5 Nm/rad 17.0 Nm/rad	5.9 10.5 17.0	239 292 346	Underneath insole
Flores et al. (2019) [34]	Exeter Research flex tester	30°	10°–30°	360°/s	30	Kalenji PT + top loaded CF plate Kalenji PT + bottom loaded CF plate	0.26 ± 0.02 Nm/° 0.28 ± 0.01 Nm/°	14.9 16.0	403.2	Insole vs. between midsole and outsole
McLeod et al. (2020) [22]	3 Point Bending Test	7.5 mm	5–6 mm	16 mm/s	5	Saucony Freedom CF plates with increasing stiffness{	8.3–10.0 N/mm 11.3–14.2 N/mm 13.0–15.4 N/mm 14.6–18.0 N/mm 16.3–25.6 N/mm 21.9–26.2 N/mm	3.3–4.0 4.5–5.7 5.2–6.2 5.8–7.2 6.5–10.2 8.8–10.5	280–299 287–314 295–315 300–318 304–321 312–333	Embedded between midsole and outsole, forefoot & midfoot
Beck et al. (2020) [23]	3 Point Bending Test	10 mm	5–9 mm	8 mm/s	3	Adidas Adizero Adios Boost 2 + 0.8 mm CF plate + 1.6 mm CF plate	13.0 ± 1.0 N/mm 31.0 ± 1.5 N/mm 43.1 ± 1.6 N/mm 84.1 ± 1.1 N/mm	5.2 12.4 33.6 17.2	Controlled	Insole
Cigoja et al 2020 [48]	3 Point Bending Test	15 mm	80-90% of the loading curve	10 mm/s	10	Nike Free 2018 + CF plate +3.2 mm CF plate	1.69 N/mm 13.44 N/mm	2.7 21.5	not reported	Underneath insole

CF carbon fiber, *EVA* ethylene–vinyl acetate, *PT* prototype, *PU* polyurethane

[18] were the first to report that increased longitudinal bending stiffness led to improved RE. A group of 13 recreational runners (10 km ≤ 40 min, ≥ 25 km/week) ran at individu- ally determined speeds (below anaerobic threshold; average 3.7 m/s) in three different shoe models. In the stiff condition (15.2 Nm/rad) RE was 0.8% better as compared to the control condition (7.2 Nm/rad); in the stiffest condition (18.0 Nm/rad) RE was not different from the control condition.

Since then, studies have reported mixed results for the effects of increased longitudinal bending stiffness on RE ranging from small deteriorations [24], to no difference [19, 21, 23], to small (~ 1%) improvements [18, 20], to more substantial (3–4%) improvements [5, 8, 9, 22] (Table 2, see Electronic Supplementary Material Appendix S1 Table S2 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table).

The largest improvements in RE have been observed by studies on the Nike Vaporfly 4% shoes, where a curved stiff carbon-fiber plate is combined with more compliant and resilient midsole foam [5]. However, as argued by Frederick [2], the observed metabolic difference between two specific shoe models "should not be treated as evidence of a more universal and broadly predictable outcome due to … [a] single feature", such as increased longitudinal bending stiffness. At 3.89, 4.44, and 5.00 m/s, Hoogkamer et al. [5] observed ~ 4% RE improvements in Nike Vaporfly prototypes (18.5 Nm/rad) over Adidas Adios Boost (7.0 Nm/rad) and Nike Streak (9.4 Nm/rad) baseline racing flats, thus providing the iconic 4% name. At 4.44 m/s, Hunter et al. [9] observed 2.8% and 1.9% improvements vs. the same Adidas and Nike baseline shoes, respectively. Barnes and Kilding [8] measured 4.2% and 2.6% improvements over the same adidas racing flats and Nike track spikes (of unreported longitudinal bending stiffness) respectively, consistent across female runners at 3.89, 4.17, and 4.44 m/s and male runners at 3.89, 4.44, and 5.00 m/s. It is important to note, as stated above, that in ecologically relevant comparisons of commercially available shoe models, observed differences in RE could partly or fully be due to additional differences in shoe properties such as mass, upper design, and midsole compliance, resilience, and geometry.

3.3 Plate Location, Speed Effects, and Critical Stiffness

Interested in assessing the effects of longitudinal bending stiffness itself, several studies used baseline control shoes and modified their stiffness by embedding carbon-fiber plates in the midsole or using carbon-fiber insoles, keep- ing other properties (e.g., upper, midsole foam, geometry, and mass) constant (see Table 1). There have been three main locations the plate has commonly been placed: (1) top loaded (plate placed as an insole or just below it); (2) embedded (in between midsole foam); (3) bottom loaded (along the sole of the shoe). There appears to be a distinction between studies that used embedded carbon-fiber plates and reported significant improvements in RE [18, 22], and studies that use top-loaded plates, and did not find overall significant RE improvements [20, 21, 23, 24]. Specifically, Flores et al. [21] and Beck et al. [23] both used top-loaded plates of similar longitudinal bending stiffness as the Vaporfly shoes, and while both studies controlled for mass, they did not observe improvements in RE as compared to control shoes. This suggests that plate location is an important factor concerning RE (also see Fig. 1 and Sect. 5.1 below, for biomechanical considerations).

Further, McLeod et al. [22] and Day and Hahn [24] have addressed how metabolically optimal shoe stiffness changes across speeds. McLeod et al. [22] tested 21 competitive male runners (10 km ≤ 36 min) at both a slow (2.89 m/s) and fast (4.47 m/s) speed with six different bending stiffness conditions (stiffness values varied slightly between individu- als based on the shoe size, see Table 1). For each speed, a second-order polynomial was fitted onto each subject's RE vs. shoe stiffness data. The stiffness at the minimum of this U-shaped curve was defined as the metabolically optimal stiffness. For a subset of 10 rearfoot strikers optimal stiffness was higher at the fast speed than at the slow speed, but overall there were no significant differences in optimal stiffness between rearfoot and midfoot strikers or between the slow and fast speed. Importantly, for a number of participants the metabolically optimal stiffness determined with the second-order polynomial was outside the tested stiffness range, particularly at the fast speed, highlighting individual differences and suggesting that future work should assess a wider range of stiffness conditions. Day and Hahn [24] also investigated the effects of longitudinal bending stiff- ness on RE across speeds. At both 3.89 and 4.72 m/s, RE was similar in control (5.9 Nm/rad) and stiff (10.5 Nm/rad) conditions. However, RE in the very stiff condition (17.0 Nm/rad) was significantly worse than the control at 3.89 m/s and significantly worse than both the control and stiff conditions at 4.72 m/s. Once again considering individual differences, more participants exhibited improved RE in the stiff condition as compared to the control condition while running at 4.72 m/s (4 out of 10 participants) as compared to 3.89 m/s (2 out of 9 participants). Importantly, mass was not controlled across footwear conditions (with the stiff and very stiff shoes weighing about 50 and 100 g more than the control shoe), which may have contributed to the lack of improvement in RE. Together these data suggest that running speed influences the optimal bending stiffness for RE, and that it might be important to look at individual responses rather than at group level.

Multiple authors have supported the concept that metabolically optimal longitudinal bending stiffness is individual. Specifically, Oh and Park [20] suggested that subjects have an individualized optimal stiffness determined by their natural MTP joint flexion. To test this, they measured individual's critical stiffness (ratio between MTP joint torque and maximum MTP joint flexion angle during the stance phase while running in flexible control shoes) and had them run in five shoe conditions with increased bending stiff- ness (Table 1). Supporting their hypothesis, they found that RE did not improve on a group level; however, there was a significant improvement (~ 1%) in shoes that most closely matched individuals' critical stiffness. Further, Madden et al. [19] also found no overall significant differences in RE by increasing bending stiffness, but discerned a 2.9% improvement in RE with the stiffer shoe condition (9.2 Nm/rad) as compared to the control (3.2 Nm/rad) when only taking into account responders. Finally, while comparing RE across Nike Vaporflys, Nike Zoom Streaks, and adidas Boosts, Hunter et al. [9] proposed that the large variation in responses (from 0.0 to 6.4% change) they observed may be due to different optimal shoe stiffnesses for individual runners. Overall, it appears that athletes may not all respond the same way to increased bending stiffness, making critical stiffness subject dependent. However, within-subject random variation related to measurement error in RE might also explain a large part of the apparent individual response differences [28].

3.3 Metabolically Optimal Longitudinal Bending Stiffness

For shoe companies, it would be useful to know if a generic metabolically optimal longitudinal bending stiffness exists. Unfortunately, the current literature suggests that metabolically optimal bending stiffness is not generic, but rather appears to depend on running speed and characteristics of the individual runner. Still, and notably, while RE improvements in the Vaporfly shoes vary substantially between individuals, very few individuals show RE decrements and the group level RE improvements are consistent from 3.9 to 5.0 m/s [5, 8, 9]. When comparing metabolically optimal bending stiffness values across studies, note that part of the variance in reported metabolically optimum bending stiffness values is likely related to methodological and study design differences both in how footwear bending stiffness is assessed and in how RE is assessed (speed, population). Furthermore, the effects of bending stiffness on RE can be blunted or amplified by other factors, such as midsole geometry.

In addition to all these factors, it is important to realize that the effect of longitudinal bending stiffness on RE (i.e., full body energetic demand) is the sum of multiple small changes in metabolic demand of many different muscle–tendon units in the feet and legs. Although increased longitudinal bending stiffness might increase the force requirements of some muscles, it might also reduce the muscle fascicle shortening velocity or elastic energy storage and return in those, or other, muscle–tendon units, each with differ- ent metabolic consequences. Below, we discuss observed changes in running biomechanics with increased longitudinal bending stiffness, and aim to relate these to metabolic changes where possible.

4 Spatiotemporal Parameters

Findings regarding the effects of longitudinal bending stiffness on stride frequency have varied. There have been reports of small, but significant decreases in stride frequency with increased bending stiffness (0.02–0.03 Hz) (Table 3, see Electronic Supplementary Material Appendix S1 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table) [5, 10, 24], but others have found no significant differences [8, 21, 23]. Similarly, the effects of longitudinal bending stiffness on ground contact time have also varied, with studies reporting increased bending stiffness leading to 1–12 ms longer contact times [5, 20, 23, 24, 29, 30] or having no significant effect [8–10, 19].

5 Joint Mechanics

5.1 Metatarsal–Phalangeal Joint

The MTP joint has been identified as an important location for energy loss in the foot during running [16, 31]. During the stance phase, the joint dorsiflexes, absorbing energy, and remains dorsiflexed through push-off, returning little to none of the energy absorbed. Accordingly, altering MTP joint mechanics through increased longitudinal bending stiffness has been a focus for improving overall energy return and improving running performance (Table 4, see Electronic Supplementary Material Appendix S1 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table).

Energy absorption, or negative work, can be reduced through decreases in the internal joint moment or slower dorsiflexion velocity. Therefore, increasing the longitudinal bending stiffness should reduce energy loss at the MTP joint as it stiffens the joint, limiting dorsiflexion. Indeed, many authors have found that increased longitudinal bending stiffness reduces MTP joint dorsiflexion [10, 19, 20, 31] and slows dorsiflexion angular velocity [10, 31] (Table 4). In

Table 2 Running economy outcomes for different longitudinal bending stiffness footwear interventions

Study	Shoe condition	Bending stiffness (Nm/rad)	Participants	Velocity (m/s)	Running economy			RE % change (for significant comparisons)	EMG (≈ no significant difference)	Participant running level
Roy and Stefanyshyn (2006) [18]	Adidas Adistar Comp + CF plate + thicker CF plate	7.2 15.0 18.0	13	3.7 average (based on $VO_{2\,max}$)	(ml/kg/min) 45.323 ± 3.032 44.960 ± 3.002 45.246 ± 3.125			Stiff vs. control: 0.80%	Soleus Gastrocnemius Biceps femoris ≈ Vastus lateralis ≈ Rectus femoris ≈	≤40 min for 10-km race ≥25 km/week
Madden et al. (2016) [19]	Adidas PT Adidas PT + CF stiffening plates	3.2 9.2	18 men	3.2 ± 0.5 (based on $VO_{2\,max}$)	(ml/kg/min) 38.1 (R: 35.9, NR: 40.4) 37.7 (R: 34.8, NR: 40.8)			For responders: stiff vs. control: 3.06%	–	Recreational athletes
Oh and Park (2017) [20]	Reebok ZQUICK + 0.8 mm CF plate + 1.2 mm CF plate + 1.5 mm CF plate + 1.8 mm CF plate + 2.0 mm CF plate	1.5 10.0 24.5 32.1 42.1 56.6	19	2.43 ± 0.23 (based on $VO_{2\,max}$)	Overall similar [graph only]			k_{cr} vs. control and stiffest: 1.1 ± 1.2%	–	Recreational athletes
Flores et al. (2019) [21]	Kalenji PU PT	6.2	19 men	3.0 ± 0.31 (90% of VAT)	(kJ/kg/km) 4.73 ± 0.51			No significant differences	–	Recreational runners
	Kalenji EVA PT	7.7			4..75 ± 0.50					
	Kalenji PU PT + 0.9 mm CF plate	15.2			4.76 ± 0.51					
	Kalenji EVA PT + 0.9 mm CF plate	17.3			4.72 ± 0.49					
Hoogkamer et al. (2018) [5]	Adidas Adizero Adios Boost 2 Nike Zoom Streak 6 Nike Vaporfly PT (curved CF plate)	7.0 9.4 18.5	18 men	3.89, 4.44, 5.00	(W/kg) 14.13 ± 0.84 14.17 ± 0.82 13.57 ± 0.76	(W/kg) 17.03 ± 1.02 17.07 ± 1.02 16.36 ± 0.99	(W/kg) 20.25 ± 1.18 20.26 ± 1.06 19.42 ± 1.08	Overall across all velocites: NVF vs. NS: 4.16% NVF vs. AB: 4.01%	-	≤32 min for 10-km race or equivalent
Barnes and Kilding (2019) [8]	Nike Zoom Matumbo 3	*< 7.0*	12 men	3.89, 4.44, 5.00	(W/kg) 15.71 ± 0.76	(W/kg) 18.39±0.87	(W/kg) 21.49±1.36	Overall across all velocities:	–	≤15 min for 5-km race
	Adidas Adizero Adios Boost 3	*7.0*			15.85 ± 0.71 15.25 ± 0.71	18.81 ± 0.91 17.99 ± 0.88	21.74 ± 1.19 20.86 ± 1.30	NVF vs. AB: 4.2 ± 1.2%		or≤30 min for 10-km race
	Nike Vaporfly	*18.5*			15.50 ± 0.63	18.15 ± 0.91	21.14 ± 1.21	NVF vs. NZM:		or equivalent

Table 2 (continued)

Study	Shoe condition	Bending stiffness (Nm/rad)	Participants	Velocity (m/s)	Running economy			RE % change (for significant comparisons)	EMG (≈ no significant difference)	Participant running level
Barnes and Kilding (2019) [8]	Nike Zoom Matumbo 3	*< 7.0*	12 women	3.89, 4.17, 4.44	15.46 ± 0.92 15.54 ± 0.95	16.86 ± 1.13 17.05 ± 1.06	18.60 ± 0.85 18.88 ± 0.86		–	≤17:15 min for 5-km race
	Adidas Adizero Adios Boost 3	*7.0*			15.01 ± 0.91 15.21 ± 0.95	16.55 ± 1.03 16.67 ± 1.06	18.24 ± 0.82 18.43 ± 0.80			≤35:30 min for 10-km
	Nike Vaporfly	*18.5*								race or
	Nike Vaporfly + (mass matched to AB)	*18.5*								equivalent
Hunter et al. (2019) [9]	Adidas Adizero Adios Boost 3	*7.0*	19 men	4.44	(ml/kg/min) 49.48 ± 2.60			NVF vs. AB: 2.8%	–	≤32 min for 10-km race or equivalent
	Nike Zoom Streak 6	*9.4*			49.05 ± 2.55			NVF vs. NS: 1.9%		
	Nike Vaporfly	*18.5*			48.11 ± 2.49					
Day and Hahn	Epic React Flyknit	5.9	10 men	3.89, 4.72	(W/kg)	(W/kg)		At 3.89 m/s:	–	≤16 min for
(2019) [24]	+ 3 mm Nylon plate + 2 × 3 mm Nylon plate	10.5 17.0			14.42 ± 1.06 14.61 ± 1.08 14.76 ± 1.07	18.21 ± 1.14 18.22 ± 1.15 18.75 ± 1.21		stiffest vs. control: − 2.36% At 4.72 m/s: stiffest vs. control: − 2.97% stiffest vs. stiff: − 2.91%		5-km race or equivalent ≥50 km/week
McLeod et al. (2020) [22]	Saucony Freedom CF plates with increasing stiffness {	3.3–4.0 4.5–5.7 5.2–6.2 5.8–7.2 6.5–10.2 8.8–10.5	21 men	2.98, 4.47	(mL/kg/min) U-shaped	(mL/kg/min) U-shaped		Optimal stiffness vs. control: at 2.98 m/s: 1.93 ± 1.82% at 4.47 m/s: 3.02 ± 2.62%	–	≤36 min for 10-km race or equivalent
Beck et al. (2020) [23]	Adidas Adizero Adios Boost 2 + 0.8 mm CF plate + 1.6 mm CF plate + 3.2 mm CF plate	4.1 12.4 17.2 33.6	15 men	3.5	(W/kg) Overall similar			No significant differences	Tibialis anterior Soleus Medial gastrocnemius Vastus medialis Rectus femoris Biceps femoris Gluteus maximus	≤25 min for 5-km race or equivalent

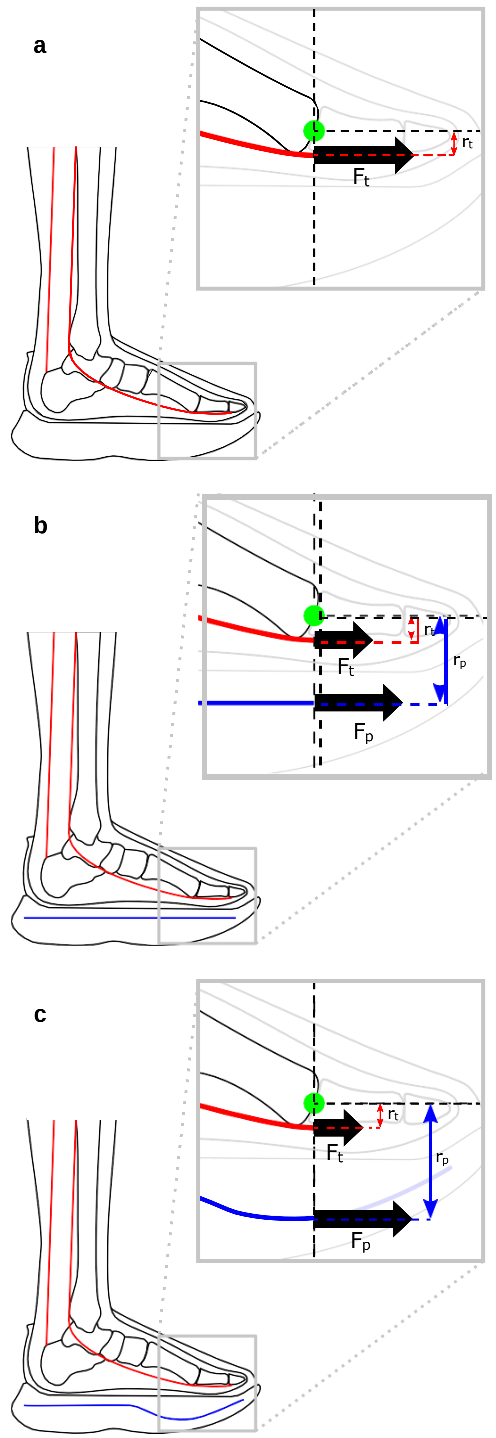

Fig. 1 Relative force contributions by tissue (intrinsic and extrinsic muscles, plantar fascia, and other connective tissue), F_t, and carbon-fiber plate, F_p, to the external joint moment at the metatarsal-phalangeal joint for **a** no plate, **b** top-loaded plate, and **c** curved plate. r_t and r_p indicate the respective moment arms

line with this, Hoogkamer et al. [10] and Cigoja et al. [30] observed decreased negative work with increased bending stiffness. Contrastingly, Willwacher et al. [32] and Roy and Stefanyshyn [18] reported no difference in negative work, and Willwacher et al. [31] reported a U-shaped relationship. In these cases, increases in plantarflexion moment exceeded decreases in dorsiflexion velocity. Therefore, an effective carbon-fiber plate should balance increased joint moments and decreased angular velocities [31]. It is important to note that plantarflexion moment is a resultant moment, counteracted by the combination of the foot and the shoe. As such, any changes in resultant moment, power, or work (or lack thereof) should not be attributed to the foot itself. However, the contribution of the shoe to external MTP joint moment, power and work can be estimated from the measured dorsiflexion angle and longitudinal bending stiffness of the shoe, and then subtracted (see [5]).

Recently, Farina et al. [33] assessed the effect of plate shape (no plate, flat, moderate curve, and extreme curve) on MTP joint mechanics. They determined that no plate resulted in the most energy lost at the MTP, with the least energy lost in the extremely curved condition. Although all plate conditions showed shortening of the negative power phase, the flat plate had an increased negative power amplitude. Two possible mechanisms help explain these findings. First, a flat plate moves the point of ground reaction force application more distally, creating a larger moment arm, and increasing the plantarflexion moment. In comparison, a curved plate allows for the ground reaction force to be applied closer to the MTP joint, reducing dorsiflexion moment while still limiting dorsiflexion angular velocity. A second mechanism is that a curved plate allows the plate to be located further from the MTP joint. Therefore, when plates have the same stiffness, a curved plate has a higher effective stiffness since it acts further from the point of rotation, creating a larger resultant moment (see Fig. 1). In fact, Flores et al. [34] recently found a bottom-loaded plate resulted in higher moments at the MTP, ankle, knee, and hip as compared to a top-loaded plate. Interestingly, the plate location had only affected the positive work performed at the knee, suggesting a reduction in joint angular velocities in the other joints. This mechanism is particularly important to consider in other studies where custom carbon insoles were created and top loaded. To date, most studies have addressed flat plates; however this evidence suggests that curved plates may have a substantial benefit over flat plates.

In addition to altering negative work, longitudinal bending stiffness has also been found to have an effect on positive work. Specifically, two studies [30, 31] have reported a significant increase in positive work with increased bending stiffness. To explain this, Cigoja et al. [30] demonstrated that increased stiffness resulted in an earlier onset of MTP joint plantarflexion. This reduces the negative power phase

Table 3 Stride frequency and contact time for different longitudinal bending stiffness footwear interventions

Study	Shoe condition	Bending stiffness (Nm/rad)	Velocity (m/s)	Stride frequency (Hz)			Contact time (s)		
Willwacher et al. (2014) [29]	Nike Free 3.0	0.3	3.5 ± 5%	-			0.239 ± 0.016*°		
	+0.9 mm CF plate	2.8					0.248 ± 0.017*		
	+3.2 mm CF plate	6.5					0.249 ± 0.015°		
Oh and Park (2017) [20]	Reebok ZQUICK	1.5	2.43 ± 0.23 (based on VO_{2max})	-			increased as bending stiffness increased [graph only]		
	+0.8 mm CF plate	10.0							
	+1.2 mm CF plate	24.5							
	+1.5 mm CF plate	32.1							
	+1.8 mm CF plate	42.1							
	+2.0 mm CF plate (n = 1)	56.6							
Flores et al. (2019) [19]	Kalenji prototype PU	6.2	3.0 ± 0.31 (90% of VAT)	1.33 ± 0.05			0.2756 ± 0.0186		
	Kalenji prototype EVA	7.7		1.34 ± 0.05			0.2719 ± 0.0177		
	Kalenji prototype PU + 0.9 mm CF plate	15.2		1.33 ± 0.05			0.2787 ± 0.0188		
	Kalenji prototype EVA + 0.9 mm CF plate	17.3		1.34 ± 0.04			0.2770 ± 0.0187		
Hoogkamer et al. (2018) [5]	Adidas Adizero Adios Boost 2	7.0	3.89, 4.44, 5.00	1.445 ± 0.075 ^{a};*	1.485 ± 0.08	1.52 ± 0.08	0.212 ± 0.008 ^{a};*	0.196 ± 0.007	0.181 ± 0.005
	Nike Zoom Streak 6	9.4		1.45 ± 0.07 ^{a};°	1.485 ± 0.075	1.525 ± 0.08	0.212 ± 0.008 ^{a};°	0.197 ± 0.008	0.180 ± 0.005
	Nike Vaporfly prototype (curved CF plate)	18.5		1.435 ± 0.07 ^{a};*°	1.48 ± 0.075	1.51 ± 0.08	0.213 ± 0.008 ^{a};*°	0.197 ± 0.007	0.182 ± 0.005
Hoogkamer et al. (2019) [10]	Adidas Adizero Adios Boost 2	7.0		1.475 ± 0.05 *			0.191 ± 0.006		
	Nike Zoom Streak 6	9.4		1.48 ± 0.045°			0.190 ± 0.005		
	Nike Vaporfly prototype (curved CF	18.5		1.455 ± 0.055 *°			0.192 ± 0.006		

Table 3 (continued)

Study	Shoe condition	Bending stiffness (Nm/rad)	Velocity (m/s)	Stride frequency (Hz)			Contact time (s)		
Barnes & Kilding			Men:	1.458 ± 0.083	1.513 ± 0.080 *	1.570 ± 0.080 *	0.221 ± 0.017 *	0.205 ± 0.016	0.194 ± 0.016
2019) [8]			3.89, 4.44, 5.00	1.458 ± 0.088	1.497 ± 0.085	1.550 ± 0.068	0.227 ± 0.017	0.212 ± 0.020	0.198 ± 0.017
				1.462 ± 0.078	1.497 ± 0.078 *	1.550 ± 0.063 *	0.227 ± 0.017 *	0.209 ± 0.017	0.197 ± 0.014
				1.458 ± 0.082	1.492 ± 0.080	1.550 ± 0.067	0.227 ± 0.016	0.209 ± 0.018	0.197 ± 0.015
	Nike Zoom	*< 7.0*		1.458 ± 0.083	1.513 ± 0.080 *	1.570 ± 0.080 *	0.221 ± 0.017 *	0.205 ± 0.016	0.194 ± 0.016
	Matumbo 3	*7.0*		1.458 ± 0.088	1.497 ± 0.085	1.550 ± 0.068	0.227 ± 0.017	0.212 ± 0.020	0.198 ± 0.017
	Adidas Adizero	*18.5*		1.462 ± 0.078	1.497 ± 0.078 *	1.550 ± 0.063 *	0.227 ± 0.017 *	0.209 ± 0.017	0.197 ± 0.014
	Adios Boost 3 Nike Vaporfly (curved CF plate) Nike Vaporfly + (mass matched to Adidas)	*18.5*		1.458 ± 0.082	1.492 ± 0.080	1.550 ± 0.067	0.227 ± 0.016	0.209 ± 0.018	0.197 ± 0.015
				1.473 ± 0.158 *° 1.457 ± 0.163 *	1.507 ± 0.142 *° 1.490 ± 0.133 *	1.513 ± 0.173 *°	0.230 ± 0.040 0.234 ± 0.040 *	0.220 ± 0.036 0.222 ± 0.035 *	0.213 ± 0.040 0.215 ± 0.036 *
				1.460 ± 0.153° 1.457 ± 0.153	1.472 ± 0.160° 1.473 ± 0.153	1.500 ± 0.163 * 1.500 ± 0.170° 1.498 ± 0.162	0.230 ± 0.042 * 0.231 ± 0.042	0.221 ± 0.040 * 0.220 ± 0.042	0.211 ± 0.039 * 0.211 ± 0.038
Hunter et al. (2019) [9]	Adidas Adizero Adios Boost 3	*7.0*	4.44	-			0.190 ± 0.004		
	Nike Zoom Streak 6	*9.4*					0.190 ± 0.004		
	Nike Vaporfly (curved CF plate)	*18.5*					0.190 ± 0.005		
Day & Hahn (2019) [24]	Epic React Flyknit	5.9	3.89, 4.72, 5.56	1.49 ± 0.06 *°	1.56 ± 0.08*	1.67 ± 0.09	0.207 ± 0.009*	0.188 ± 0.010	0.165 ± 0.009 *°
	+ 3 mm Nylon 11 plate	10.5		1.47 ± 0.06 *	1.54 ± 0.08	1.66 ± 0.09	0.210 ± 0.011	0.188 ± 0.010	0.169 ± 0.010 *
	+ 2 × 3 mm Nylon plate	17.0		1.46 ± 0.06°	1.54 ± 0.08 *	1.67 ± 0.09	0.212 ± 0.011 *	0.189 ± 0.011	0.170 ± 0.010°
Cigoja et al. (2019) [30]	Nike Free 5.0	1.9	3.5	–			0.2396 ± 0.0189 *		
	+ CF plate	19.0					0.2520 ± 0.0177 *		
Beck et al. (2020)	Adidas Adizero	5.2	3.5	step time, no			increased as bending		

Table 4 (continued)

Study	Shoe condition	Bending stiffness (Nm/rad)	Velocity (m/s)	MTP Angle (deg)	Angular velocity (deg/sec)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Power (W/kg)	Moment arm (mm)
Beck et al. (2020) [23]	Adidas Adizero Adios Boost 2	5.2	3.5	Similar [graph only]	–	Similar [graph only]	–	–	–	–
	+ 0.8 mm CF plate	12.4								
	+ 1.6 mm CF plate	17.2								
	+ 3.2 mm CF plate	33.6								
Cigoja et al. (2020) [48]	Nike Free 2018 + CF plate	2.7 21.5	90% LT	–	–	–	–	(% total) 1.18 ± 0.52 4.47 ± 1.39	–	–

Matching symbols between conditions (*/°) indicate values that are significantly different

Matching symbols between conditions (* / °) indicate values that are significantly different

BL bottom loaded, *CF* carbon fiber, *EVA* ethylene–vinyl acetate, *PT* prototype, *PU* polyurethane, *RCP* respiratory compensation point, *TL* top loaded, *VAT* ventilatory anaerobic threshold

and allows for more time for positive power to be generated. Further, they showed increased MTP joint plantarflexion moments, which may be a result of passive forces in the foot arch, midsole and/or carbon-fiber plate, or from muscle contractions [10, 30, 31]. In line with this, Hoogkamer et al. [10] reported increased positive work towards the end of the stance phase with increased bending stiffness; however, these differences were not significant. These findings provide evidence for elastic storage and return, or the controversial spring function, of the plate, returning one-third of the stored mechanical energy at a rate of 0.007 W/kg, or ~ 0.16 J/step. However, as Hoogkamer et al. [10] point out, the energy stored and returned from the carbon-fiber plate itself has a minimal effect (~ 0.3% of the positive work done at the ankle) suggesting that the plate does not primarily act as a spring; rather its main contribution is likely to stiffen the MTP joint.

5.2 Ankle Joint

The triceps surae containing the soleus, medial gastrocnemius and lateral gastrocnemius merge into a common highly compliant tendon spanning the ankle joint. Hence, ankle power during running is primarily absorbed and produced by these plantar flexor muscle–tendon units. Three mechanisms have been proposed through which the complaint series elastic element (SEE) of the triceps surae muscle–tendon unit aids in reducing the metabolic cost of running. First, the compliant SEE can store and return elastic energy during the stance phase [35–37]. Next, the compliant SEE ena- bles the uncoupling of the muscle length changes from the entire muscle–tendon unit length changes [38–40]; therefore, creating more optimal working conditions for the muscle (force–length and force–velocity relationship). Lastly, the long SEE implies short muscle fibers reducing the cost of force production but also shifts the shank's center of mass more proximally, reducing the moment of inertia and as such reducing the cost of leg swing [41–43]. The triceps surae is estimated to consume between 22 and 32% of the total whole-body metabolic energy [44]. Hence, if a change in longitudinal bending stiffness can induce a reduction in triceps surae metabolic energy consumption, it will likely result in a reduced whole-body metabolic energy consumption and thus better RE. Moreover, it has been postulated that the morphology of the triceps surae muscle–tendon unit (i.e., long compliant elastic tissue and short muscle fibers) allows for more efficient work production around the ankle joint compared to the more proximal knee or hip joint lacking these long compliant in series connected elastic tissues [45, 46].

During prolonged running, positive work contribution shifts from the ankle towards the knee [47, 48], possibly explaining deteriorations in RE observed during prolonged

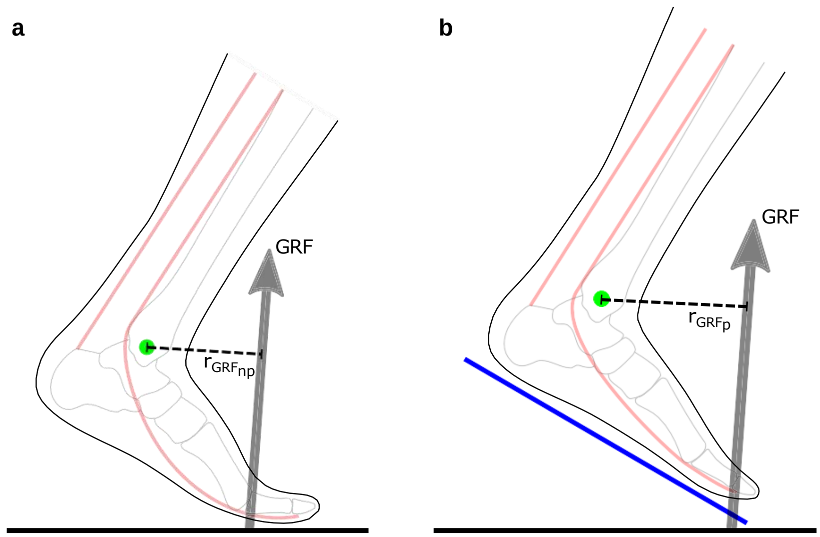

Fig. 2 In (**b**), increased longitudinal bending stiffness with a carbon-fiber plate (p) shifts the point of force application anteriorly and increases the ground reaction force (GRF) moment arm (r_{GRF}) around the ankle joint, as compared to (**a**) no plate (np)

running in some (e.g., [49]), but not all studies (for review see [50]). Cigoja et al. [48] found that when running in shoes with increased longitudinal bending stiffness the onset of the joint work redistribution from the ankle to the knee joint was delayed. Indirectly, these results suggest that increas- ing longitudinal bending stiffness may delay or reduce RE deteriorations during prolonged running. A future study may directly assess the effect of increased longitudinal bending stiffness on RE during prolonged running.

Theoretically, the metabolic effect of increased longitudinal bending stiffness on the triceps surae muscle-tendon unit appears to be an interplay of two phenomena: 1) Increased bending stiffness likely increases the external moment arm of the ground reaction force (GRF) around the ankle joint, which likely increases the ankle joint moment and the force demand (increasing metabolic demand); 2) The increased external ankle moment arm also likely reduces the ankle angular velocity and the muscle fascicle shortening velocity (reducing metabolic demand).

5.2.1 Ankle Joint Moment

The foot acts as a lever arm for the triceps surae muscles during running. Gearing ratio can be defined as the ratio of the moment arm of the external ground reaction force to the internal muscle–tendon unit moment arm [29]. The ground reaction force moves considerably during ground contact, whereas the muscle–tendon unit moment arm undergoes much less change during ground contact, implying variable gearing [51].

Although increasing longitudinal bending stiffness will shift the point of force application more anteriorly, increasing a runner's gear ratio (see Fig. 2) [20, 29, 32], the effect on the ankle joint moment is less clear. By increasing the gear ratio during running, one would expect that also the ankle joint moment in the sagittal plane would increase. However, so far only Roy and Stefanyshyn [18] reported an increased peak ankle joint moment with increased longitudinal bending stiffness during constant speed running on a 1% inclined treadmill (Table 5, see Electronic Supplementary Material Appendix S1 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table). In contrast, other studies did not find a difference in peak ankle joint moment [23, 52] or average ankle joint moment [23, 32]. Moreover, Willwacher et al. [29] demonstrated that average ankle joint moment was reduced when running in a medium stiff shoe compared to the control (less stiff) shoe or stiffest shoe. They did not find any difference in average ankle joint moment between the control and stiffest condition. Recently, Farina and colleagues [33] demonstrated that the curvature of the carbon fiber insole modulates the effects of stiffness on peak ankle joint moment. A flat carbon-fiber plate increased peak ankle joint moment compared to the control shoe whereas a moderately or extremely curved carbon-fiber plate did not alter peak ankle joint moment compared to the control condition. In addition, they established that adding curvature to a carbon insole can reduce the MTP joint energy loss without increasing peak ankle joint moment (see Sect. 5.1 above). Furthermore, longitudinal bending stiffness did not alter positive work, negative work or average power at the ankle joint [30, 32].

Table 5 Ankle joint mechanics for different longitudinal bending stiffness footwear interventions

Study	Shoe condition	Bending stiffness (Nm/rad)	Velocity (m/s)	Ankle						
				Angle (deg)	Angular velocity (deg/s)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Power (W)	Moment arm (mm)
Roy and Stefanyshyn (2006) [18]	Adidas Adistar Comp	7.2	3.7 (based on $VO_{2\,max}$)	–	–	231.3 ± 24.7*	(J) [graph only]	Similar [graph only]	–	–
	+ CF plate	15.2				235.9 ± 24.7*	– 64.4 ± 13.0*			
	+ thicker CF plate	18.0				240.6 ± 26.5*	– 71.2 ± 13.8*			
Willwacher et al. (2013) [31]	Nike Free 3.0 + 0.9 mm CF plate + 3.2 mm CF plate	0.3 2.8 6.5	3.5 ± 5%	–	–	–	–	–	–	–
Willwacher et al. (2014) [29]	Nike Free 3.0 + 0.9 mm CF plate + 3.2 mm CF plate	0.3 2.8 6.5	3.5 ± 5%	–	–	(Nm/kg) – 1.58 ± 0.24* – 1.52 ± 0.29*° – 1.61 ± 0.18°	–	–	–	136.1 ± 10.6* 148.2 ± 8.9* 157.4 ± 6.5*
Madden et al. (2016) [19]	Adidas PT Adidas PT + CF stiffening plates	3.2 9.2	3.2 ± 0.5 (based on $VO_{2\,max}$)	14.4 13.5	290* 275*	–	–	–	–	–
Oh and Park	Reebok ZQUICK	1.5	2.43 ± 0.23	–	–	–	–	–	–	Increased with
(2017) [20]	+ 0.8 mm CF plate	10.0	(based on $VO_{2\,max}$)							increased stiffness [graph only]
	+ 1.2 mm CF plate	24.5								
	+ 1.5 mm CF plate	32.1								
	+ 1.8 mm CF plate	42.1								
	+ 2.0 mm CF plate (n = 1)	56.6								
Hoogkamer et al. (2019) [10]	Adidas Adizero Adios Boost 2 Nike Zoom Streak 6 Nike Vaporfly PT (curved CF plate)	7.0 9.4 18.5	4.44	21.2 ± 5.3* 19.3 ± 4.0° 17.5 ± 3.9*°	Similar [graph only]	264.6 ± 27.7* 260.6 ± 23.2 254.5 ± 28.1*	(J/kg/step) – 0.87 ± 0.09* – 0.80 ± 0.10* – 0.72 ± 0.07*	(J/kg/step) 0.92 ± 0.14* 0..93 ± 0.19° 0.83 ± 0.16*°	[graph only]	Similar [graph only]
Cigoja et al.	Nike Free 5.0	1.9	3.5	–	–	–	– 0.46 ± 0.11	0.77 ± 0.14	–	–
(2019) [30]	+ CF plate	19.0					– 0.46 ± 0.09	0.74 ± 0.11		
Flores et al. (2019) [34]	Kalenji PT + top loaded CF plate	14.9	3.28 ± 0.28 (based on VAT)	BL > TL [graph only]	–	BL > TL [graph only]	– 0.485 ± 0.181 – 0.481 ± 0.184 – 0.535 ± 0.163 – 0.541 ± 0.163	0.736 ± 0.134 0.725 ± 0.137 0.772 ± 0.138 0.775 ± 0.136	–	–
	Kalenji PT + bottom loaded CF plate	16.0	4.01 ± 0.27 (based on VAT and							

Table 5 (continued)

Study	Shoe condition	Bending stiffness (Nm/rad)	Velocity (m/s)	Ankle Angle (deg)	Angular velocity (deg/s)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Power (W)	Moment arm (mm)
Beck et al. (2020) [23]	Adidas Adizero Adios Boost 2	5.2	3.5	Similar [graph only]	–	Similar [graph only]	–	–	–	–
	+0.8 mm CF plate	12.4								
	+1.6 mm CF plate	17.2								
	+3.2 mm CF plate	33.6								
Cigoja et al. (2020) [48]	Nike Free 2018	2.7	90% LT	–	–	–	–	(% total) 47.83 ± 8.31	–	–
	+ CF plate	21.5						47.78 ± 9.39		

BL bottom loaded, *CF* carbon fiber, *EVA* ethylene–vinyl acetate, *PT* prototype, *PU* polyurethane, *RCP* respiratory compensation point, *TL* top loaded, *VAT* ventilatory anaerobic threshold

Matching symbols between conditions (*/°) indicate values that are significantly different

5.2.1 Triceps Surae Muscle Fascicle Shortening Velocity

When running at a fixed speed, a greater ankle moment arm from increased longitudinal bending stiffness is likely to reduce ankle plantarflexion velocity, and hence induce slower triceps surae muscle-tendon unit contraction (Fig. 3). Indeed, running in shoes with increased longitudinal bending stiffness often increases ground contact time (Table 3) [5, 20, 23, 24, 29, 30]. Slower muscle contractions are more force efficient and will therefore reduce a muscle's metabolic energy consumption [53, 54]. Madden and colleagues [19] showed that a subset of runners who enhanced their RE when running in shoes with greater longitudinal bending stiffness demonstrated reduced angular velocity of the ankle joint whereas runners whose RE worsened had no change in ankle angular velocity. Similarly, Cigoja et al. [30] showed that the triceps surae muscle-tendon unit shortening velocity was reduced in stiff compared to control shoes. These studies seem to suggest that triceps surae muscle contraction velocity may be reduced, implying more force-efficient force production and therefore better RE.

Yet, these studies are based on kinematic data, whereas modern ultrasound imaging allows to directly investigate in vivo muscle fiber length changes of the triceps surae muscle. Takahashi and colleagues [55] used ultrasound imaging to study the effect of longitudinal bending stiffness on soleus muscle fiber length and velocities during walking. Increasing longitudinal bending during walking at typical speed (1.25 m/s) reduces soleus contraction velocity but increases its peak force, eventually resulting in more energy consumption while walking with the stiffest insole. A follow-up study investigating different walking speeds revealed that at a faster walking speed (2 m/s), when fascicle shortening velocities are higher compared to the typical walking speed, walking with the stiffest shoe reduced energy consumption [56]. In contrast, Beck et al. [23] did not find a difference in soleus muscle operating length, contraction velocity, pennation angle, force, or activation while running in shoes with added longitudinal bending stiffness. Moreover, the authors could not detect differences in metabolic energy consumption between shoe conditions. However, the fact that the authors did not detect a change in gear ratio or ankle joint angles or moments suggests that the biomechanics were not altered enough to expect changes in soleus contraction dynamics or energy consumption. Therefore, it remains possible that in the studies demonstrating changes in gear ratio and ankle joint moment when running in shoes with greater longitudinal bending stiffness [8, 18, 29, 34], triceps surae muscle dynamics were altered. Additional studies should further elucidate this topic.

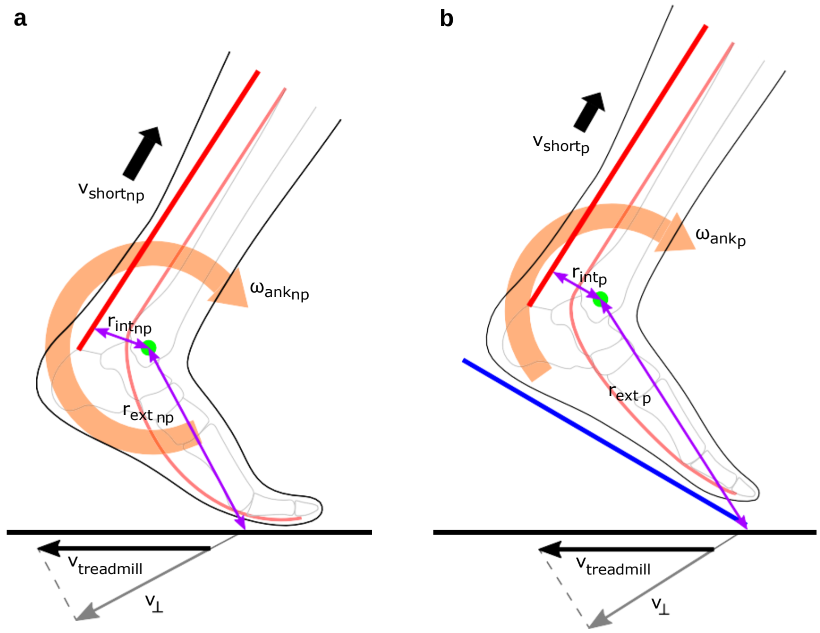

Fig. 3 At a fixed running speed ($V_{treadmill}$), in (**b**) the increased longitudinal bending stiffness from a carbon-fiber plate (p) increases the ankle external moment arm (r_{ext}) which reduces ankle plantarflexion velocity (ω_{ank}), inducing slower triceps surae muscle-tendon unit shortening velocity (V_{short}), as compared to (**a**) no plate (np). Internal moment arm (r_{int}) will be similar in both conditions

5.2.1 Triceps Surae Strength

The effect of increasing longitudinal bending stiffness on the ankle joint might depend on a subject's muscle strength. Willwacher et al. [29] identified two strategies by which subjects adapt when running in shoes with higher longitudinal bending stiffness during constant speed running. Either the subject increases the ankle joint moment and keeps ground contact time constant, or the subject does not increase joint moment but increases push-off time. They suggested that this individual difference may reflect triceps surae strength capabilities, with subjects increasing ground contact time instead of increasing ankle joint moment lacking strength. In addition, in a study by the same group [32] investigating the effects of longitudinal bending stiffness on the acceleration phase during sprinting, the stiffest shoe reduced acceleration performance compared to the control shoe. While the ankle gear ratio was increased in the stiffest vs. control shoe, average ankle moment and power were not, suggesting that the participants did not have the triceps surae muscle strength to benefit from the increased gear ratio.

5.2.2 Optimal Gearing and Running Speed

As discussed in Sect. 3.3 the effect of longitudinal bending stiffness on RE might be speed dependent. For walking, Ray and Takahashi [56] demonstrated that increased longitudinal bending stiffness reduced metabolic energy consumption during fast walking, whereas the same stiffness increased metabolic energy consumption at a more typical walking speed. The proposed mechanism for the reduced metabolic energy consumption during fast walking is a reduction in soleus fascicle shortening with increased stiffness. The authors suggest that during fast walking the increased longitudinal bending stiffness provides the subjects with "an extra gear" not provided by the human foot. However, one should be careful with extrapolating those results to running since soleus fascicle shortening during stance is smaller (and more consistent) across running speeds compared to fast walking [40]. The increased triceps surae shortening velocities with increasing running speeds are rather related to shorter ground contact time [40, 57], whereas in walking this is a combined effect of both shorter ground contact time and increased shortening during ground contact [40]. Still it is possible that metabolically optimal gear ratio, associ- ated with the metabolically optimal longitudinal bending stiffness, increases for faster running speeds. Yet, altering the gearing around the ankle will also affect other joints and therefore additional studies addressing the interplay between gearing and running speed will further help to understand this issue.

5.3 Knee and Hip Joints

Few studies have addressed how longitudinal bending stiffness affects hip and knee mechanics. Very few changes have been found at the knee joint (Table 6, see Electronic Supplementary Material Appendix S1 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table).

Table 6 Knee joint mechanics for different longitudinal bending stiffness footwear interventions

Study	Shoe Conditions	Bending stiffness (Nm/rad)	Velocity (m/s)	Knee Angle (deg)	Knee Angular velocity (deg/sec)	Knee Moment (Nm)	Knee Negative work (J/kg)	Knee Positive work (J/kg)	Knee Moment arm (mm)
Roy and Stefanyshyn (2006) [18]	Adidas Adistar Comp + CF plate + thicker CF plate	7.2 15.2 18.0	3.7 (based on $VO_{2\,max}$)	–	–	Similar [graph only]	Similar [graph only]	Similar [graph only]	–
Willwacher et al. (2013) [29]	Nike Free 3.0 + 0.9 mm CF plate + 3.2 mm CF plate	0.3 2.8 6.5	3.5 ± 5%	–	–	–	–	–	11.4 ± 24.0*° 29.4 ± 21.8* 34.7 ± 18.0°
Madden et al. (2016) [19]	Adidas PT Adidas PT + CF stiffening plates	3.2 9.2	3.2 ± 0.5 (based on $VO_{2\,max}$)	36.1 35.1	251 257	–	–	–	–
Hoogkamer et al. (2019) [10]	Adidas Adizero Adios Boost 2 Nike Zoom Streak 6 Nike Vaporfly PT (curved CF plate)	7.0 9.4 18.5	4.44	43.2 ± 4.0 43.4 ± 4.3 43.1 ± 4.4	Similar [graph only]	176.0 ± 26.4 174.0 ± 22.8 175.5 ± 25.5	− 0.53 ± 0.15 − 0.56 ± 0.15 − 0.53 ± 0.15	0.23 ± 0.09 0.24 ± 0.09 0.22 ± 0.08	–
Cigoja et al. (2019) [30]	Nike Free 5.0 + CF plate	1.9 19.0	3.5	–	–	–	− 0.60 ± 0.17 − 0.61 ± 0.15	0.22 ± 0.01* 0.20 ± 0.05*	–
Flores et al. (2019) [34]	Kalenji PT + top loaded CF plate Kalenji PT + bottom loaded CF plate	14.0 16.0	3.28 ± 0.28 (based on VAT) 4.01 ± 0.27 (based on VAT and RCP)	–	–	–	− 0.500 ± 0.132 − 0.495 ± 0.130 − 0.496 ± 0.153 − 0.522 ± 0.151	0.377 ± 0.099[a];* 0.383 ± 0.097[a];* 0.380 ± 0.099	–
Beck et al. (2020) [23]	Adidas Adizero Adios Boost 2 + 0.8 mm CF plate + 1.6 mm CF plate + 3.2 mm CF plate	5.2 12.4 17.2 33.6	3.5	Similar [graph only]	–	Similar [graph only]	–	0.414 ± 0.104[a];*	–
Cigoja et al. (2020) [48]	Nike Free 2018 + CF plate	2.7 21.5	90% LT	–	–	–	–	(% total) 29.06 ± 11.21 27.08 ± 11.24	–

BL bottom loaded, *CF* carbon fiber, *EVA* ethylene–vinyl acetate, *PT* prototype, *PU* polyurethane, *RCP* respiratory compensation point, *TL* top loaded, *VAT* ventilatory anaerobic threshold, *LT* lactate threshold

Matching symbols between conditions (* / °) indicate values that are significantly different

[a]Indicates main effect for condition (across all speeds)

Table 7 Hip joint mechanics for different longitudinal bending stiffness footwear interventions

Study	Shoe Conditions	Bending stiffness (Nm/rad)	Velocity (m/s)	Hip: Angle (deg)	Angular velocity (deg/s)	Moment (Nm)	Negative work (J/kg)	Positive work (J/kg)	Moment arm (mm)
Roy and Stefanyshyn (2006) [18]	Adidas Adistar Comp	7.2	3.7 (based on $VO_{2\,max}$)	–	–	Similar [graph only]	Similar [graph only]	Similar [graph only]	–
	+ CF plate	15.2							
	+ thicker CF plate	18.0							
Willwacher et al. (2014) [29]	Nike Free 3.0	0.3	3.5 ± 5%	–	–	–	–	–	80.3 ± 31.3*°
	+ 0.9 mm CF plate	2.8							94.3 ± 27.3*
	+ 3.2 mm CF plate	6.5							100.5 ± 19.7°
Madden et al. (2016) [19]	Adidas PT	3.2	3.2 ± 0.5 (based on $VO_{2\,max}$)	–	–	–	–	–	–
	Adidas PT + CF stiffening plates	9.2							
Hoogkamer et al. (2019) [10]	Adidas Adizero Adios Boost 2	7.0	4.44	Similar [graph only]	Similar [graph only]	Similar [graph only]	– 0.12 ± 0.15	0.19 ± 0.16	–
	Nike Zoom Streak 6	9.4					– 0.12 ± 0.14	0.18 ± 0.15	
	Nike Vaporfly PT	18.5					– 0.10 ± 0.11	0.18 ± 0.15	
Cigoja et al. (2019) [30]	Nike Free 5.0 (curved CF plate)	1.9	3.5	–	–	–	– 0.09 ± 0.07	0.23 ± 0.01	–
	+ CF plate	19.0					– 0.10 ± 0.06	0.24 ± 0.10	
Flores et al. (2019) [34]	Kalenji PT + top loaded CF plate	14.9 16.0	3.28 ± 0.28 (based on VAT)	–	–	–	– 0.173 ± 0.097 – 0.179 ± 0.102	0.111 ± 0.057 0.113 ± 0.054	–
	Kalenji PT + bottom loaded CF plate		4.01 ± 0.27 (based on VAT and RCP)				– 0.220 ± 0.100 – 0.228 ± 0.106	0.148 ± 0.067 0.155 ± 0.062	
Beck et al. (2020) [23]	Adidas Adizero Adios Boost 2	5.2	3.5	Similar [graph only]	–	Similar [graph only]	–	–	–
	+ 0.8 mm CF plate	12.4							
	+ 1.6 mm CF plate	17.2							
	+ 3.2 mm CF plate	33.6							
Cigoja et al. (2020) [48]	Nike Free 2018	2.7	90% LT	–	–	–	–	(% total) 21.30 ± 10.81	–
	+ CF plate	21.5						19.95 ± 8.40	

BL bottom loaded, *CF* carbon fiber, *EVA* ethylene–vinyl acetate, *PT* prototype, *PU* polyurethane, *RCP* respiratory compensation point, *TL* top loaded, *VAT* ventilatory anaerobic threshold

Matching symbols between conditions (*/°) indicate values that are significantly different

[a]Indicates main effect for condition (across all speeds)

Willwacher et al. [29] found increased longitudinal bending stiffness reduced lever arms at the knee during push-off at constant velocity running (3.3 m/s). Interestingly, in a later study Willwacher et al. [32] found no difference when studying kinematics during maximum acceleration sprints. Cigoja et al. [30] has been the only study to report decreased positive work at the knee with increased longitudinal bending stiffness, suggesting that increased stiffness redistributes positive lower joint work from the knee to the MTP. However, in a previous study, Hoogkamer et al. [10] also explored knee power but did not find any differences. One explanation for this is the stiff shoes in Cigoja et al. [30] were ten times stiffer than the control shoe, whereas in Hoogkamer et al. [10] the shoes were twice as stiff as the control [30]. No differences in knee angle [10, 19, 23], angular velocity [10, 19], moment [10, 18, 23, 32], negative work [10, 18, 30], or power [32] have been found (Table 6, see Electronic Supplementary Material Appendix S1 for 1-page table and Electronic Supplementary Material Appendix S2 for all information reported in this article combined in a single table). Only one study has reported changes with increased longitudinal bending stiffness at the hip joint [29]; specifically, hip moment arm increased. Others have found no difference in angle [10, 23], angular velocity [10], moment [10, 18, 23, 32], work [10, 18], or power [32] (Table 7). Overall, these results suggest that longitudinal bending stiffness primarily affects MTP and ankle mechanics, with small, if any, effect on the knee and hip joints.

6 Injury

To date, no study has specifically addressed the effect of carbon-fiber plates on injuries [16]. Rather, studies have quantified parameters that others have indicated as injury risk factors. For example, Firminger et al. [58] used a probabilistic model to assess the effect of increased bending stiffness on Achilles tendinopathy risk. They determined that running with stiffer footwear does not increase Achilles tendon strain, and in turn, Achilles tendinopathy risk. Others have quantified variables associated with risk factors such as ground reaction forces, joint loading rates, ankle joint moments, and knee joint moments. However, whether the magnitude of the reported changes in these outcomes have a strong effect on injury risk is not known and is often debatable. Longitudinal studies on the effect of bending stiffness on injury rates are needed to address this gap in the literature.

7 Conclusions and Future Perspectives

In conclusion, the current literature suggests that appropriate placement (top-loaded vs. embedded vs. bottom-loaded) and shape (flat vs. curved) of a carbon-fiber plate that sufficiently increases the longitudinal bending stiffness of footwear can improve RE. Metabolically optimal bending stiffness appears to depend on a combination of factors such as running speed and individual-specific characteristics. For future research focusing on such individual responses, we suggest performing multiple trials in the same footwear condition [5, 8, 9, 18, 24] to improve resolution, to determine a priori what the minimal response is to be considered a responder, and to explore potential order effects, specifically when many trials at high intensity are performed. Further research investigating how a carbon-fiber plate interacts with other footwear features (such as foam and midsole geometry), scaling of those with shoe size, body mass and strike pattern, and comparing various plate placements is needed to better understand how longitudinal bending stiffness affects RE.

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Data availability All the data discussed in this manuscript are provided in the tables.

Author contributions Conceptualization: WH; Literature search: JAO, LH, WS; Writing—original draft preparation: JAO, LH, WS, WH; Writing—review and editing: JAO, LH, WS, WH.

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2.3. UPHILL RUNNING

2.3.1 Biomechanics and Physiology

A review article summarized the biomechanics and physiology associated with uphill running (Vernillo et al., 2017). In uphill running there are some general differences as compared to level running such as higher step frequency, increased internal mechanical work, shorter swing phase duration, greater duty factor, progressive adoption to a mid- to fore-foot strike pattern, and increased power output at all joints, particularly the hip (Table 2.3.1).

Study	N	Running speed (km·h^{-1})^{a}	Slope (%)	CT	AT	DF	SF	SL
DeVita et al. [26]	13	12.1	+17.4	-	-	-	-	↗
		12.1	-17.4	-	-	-	-	↘
Gottschall and Kram [10]	10	10.8	+15.8	→→	→→	↗→	↗→	↘→
		10.8	+10.5	→→	→→	→→	→→	→→
		10.8	+5.2	→→	→→	→→	→→	→→
		10.8	-5.2	→→	→→	→→	→→	→→
		10.8	-10.5	→→	→→	→→	→→	→→
		10.8	-15.8	→→	→→	→→	→→	→→
Lussiana et al. [19]	14	10.0	+8.0	→→	→↘-8/5	-	→↗	-
		10.0	+5.0	→→	→↘-8/5	-	→↗	-
		10.0	+2.0	→→	→↘-8/5	-	→↗-8/5	-
		10.0	-2.0	→→	→→	-	→↘-8/5	-
		10.0	-5.0	→→	↗↗	-	↘↘	-
		10.0	-8.0	→→	↗↗	-	↘↘	-
Padulo et al. [20]	16	14.0	+2.0	→	→	-	→	→
		15.0	+2.0	→	↘	-	↗	↘
		16.0	+2.0	→	↘	-	↗	↘
		17.0	+2.0	→	↘	-	↗	↘
		18.0	+2.0	→	↘	-	↗	↘
		14.0	+7.0	→	↘	-	↗	↘
		15.0	+7.0	→	↘	-	↗	↘
		16.0	+7.0	→	↘	-	↗	↘
		17.0	+7.0	→	↘	-	↗	↘
		18.0	+7.0	→	↘	-	↗	↘
Padulo et al. [22]	18	15.0	+2.0	→	→	-	↗	↘
		15.0	+7.0	→	↘	-	↗	↘
Padulo et al. [21]	65	70% VO_2max	+2.0	↘	↘	↗	↗	↘
			+7.0	↗	↘	↗	↗	↘
Snyder and Farley [14]	9	10.1	+5.2	-	-	-	→→	-
		10.1	-5.2	-	-	-	→→	-
Swanson and Caldwell [23]	12	16.2	+30.0	-	-	↗	↗	-
Telhan et al. [24]	19	11.0	+7.0	-	-	-	→→	→→
		11.0	-7.0	-	-	-	→→	→→

Table 2.3.1: Summary of spatiotemporal variables during uphill running
N number of subjects, CT contact time, AT aerial time, DF duty factor, SF step frequency, SL step length (Table from Vernillo et al., 2017).

With an increase in net mechanical energy generation required to overcome the potential energy associated with slope, there is an increase in metabolic demand as slope increases (Figure 2.3.1) (Vernillo et al., 2017). The dominating factor in the metabolic rate of level and uphill running is distinct. The metabolic demand of level running is dominated by generating force for supporting body weight (Kram and Taylor, 1990). This is not the case for steep uphill running, during which metabolic rate is dominated by the cost of generating mechanical work to increase gravitational potential energy of the center of mass (Margaria et al., 1963). Taking these two concepts in consideration, Hoogkamer et al developed the following equation to predict the metabolic demand of uphill running as a function of grade and running speed (Hoogkamer et al., 2014):

$$Net\ CoT\ \left(J/(kg \cdot m)\right) = 2.70 + 0.674 \cdot e^{-18.24 \cdot \sin(\theta)} + \frac{g}{0.294} \cdot \sin(\theta)$$

Running speed also influences graded running (Khassetarash et al., 2020; Padulo et al., 2012; Vernillo et al., 2020). Overall, Vernillo et al observed speed × grade interactions pertaining to spatiotemporal parameters, ground reaction forces, and muscle activations (Vernillo et al., 2020). As speed and slope increased, step frequency increased and aerial time decreased (Padulo et al., 2012; Vernillo et al., 2020). Contact time decreased at faster speeds but was similar across inclines (Padulo et al., 2012; Vernillo et al., 2020). Moreover, peak GRFs were similar, impulse in the normal direction decreased, and average loading rate increased during uphill running across speeds (Vernillo et al., 2020). Furthermore, negative parallel impulse decreased with running speed during uphill running and level running. Positive parallel impulse also decreased with running speed during uphill running, but increased during uphill running (Vernillo et al., 2020). Overall, Khassetarash et al observed speed × grade interactions with ankle, knee, and hip kinetics, while speed did not substantially modulate the joint kinematics of graded running (Khassetarash et al., 2020). They demonstrated how the hip, knee, and ankle joints all contribute to graded running, but the hip specifically was emphasized in its importance for energy absorption and generation (Khassetarash et al., 2020).

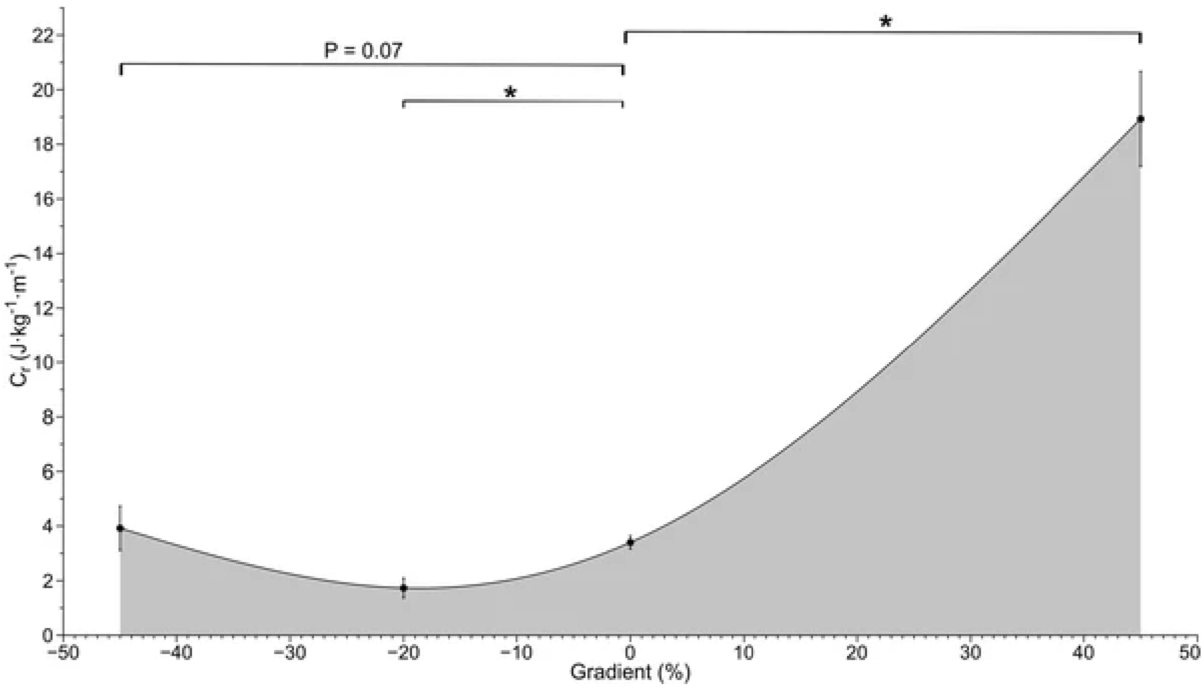

Figure 2.3.1: Relationship between metabolic cost of running (Cr) and grade (%)
There is an increase in metabolic demand as slope increases (Figure from Vernillo et al., 2017, based on data from Minetti et al., 2002).

2.3.2 Effects of Footwear LBS

Regarding footwear, there have been no studies to date that have specifically investigated the isolated effects of midsole longitudinal bending stiffness on running economy and biomechanics during uphill running. Initially, Lussiana et al. compared the effects of a minimal shoe and a traditional shoe on running economy and kinematics (Lussiana et al., 2013). They had participants run at +2%, +5%, and +8% inclines and found RE was on average 1.3% lower with the minimal shoes than the traditional shoes. Nevertheless, they attribute this significant difference in RE likely due to the differences in mass between the minimal shoe (186.9 ± 9.2 g) and traditional shoe (333.4 ± 13.9 g). In addition, Vercruyssen et al also investigated the effects of minimalist running shoes on uphill running (Vercruyssen et al., 2016). They compared minimalist running shoes, mass-controlled minimalist running shoes, and traditional running shoes. They found that, after an

18.4 km trail run exercise, compared to traditional running shoes, the minimalist running shoes and the mass-controlled minimalist running shoes resulted in significantly better running economy at level running before and after the trail run exercise. At the uphill (+10% grade) running condition, all footwear conditions compared to one another resulted in similar running economies before and after the trail run exercise.

Moreover, to expand upon the findings of Hoogkamer et al. (Hoogkamer et al., 2017), Whiting et al. (Whiting et al., 2021) compared the carbon-plated Nike Vaporfly shoes against the more conventional Nike Streak 6 shoes during shallow uphill running. Similar to level running, they found that the Nike Vaporfly had a significant effect on metabolic power during graded running. Compared to the Nike Streak, they found a 2.8% improvement in metabolic power while running at 3.61 m/s on a 3° incline. Furthermore, Hunter et al. performed a similar study comparing the effects of the carbon-plated Saucony Endorphin Pro and the more conventional Saucony Type A on metabolic power while running at a 4% grade (Hunter et al., 2022). They found a significant 1.5% improvement during running in their carbon-plated shoes, both during level and uphill running. However, they did not find any metabolic differences between their level and graded running conditions while running in their carbon-plated shoes. Both Whiting et al. and Hunter et al. found considerable energetic effects during graded running in high LBS footwear, but their findings were likely influenced by the confounding effects of differences with midsole foam properties and overall construction.

CHAPTER 3

METHODS

3.1 FOOTWEAR

Participants ran in two versions of the Nike Vaporfly 4% shoe: 1) a retail pair standard with the carbon-fiber plate intact (VF_{intact}), and 2) a retail pair altered with six mediolateral cuts through the midsole at the forefoot area (VF_{cut}). Using a table saw with a ~1.5 mm blade, angled cuts were made through the midsole and just past the carbon-fiber plate to decrease the longitudinal bending stiffness of the shoes (Figure 3.1.1). From distal to proximal, the angles of the cuts were approximately 85°, 80°, 75°, 70°, 80°, and 80°, respectively. The midsole stack height at the forefoot was ~25 mm. Given the curved shape of the carbon-fiber plate, the depth of the cuts ranged from ~10-15 mm. The bending stiffness of these two footwear conditions was measured in flexion. A standard flex tester (Shoe Flexer, Exeter Research, Brentwood NH) was used for the flexion LBS measurement, calculating flexion stiffness for the final five of fifty 30-degree flexion cycles. A material testing machine (Instron ElectroPuls 10000, Norwood, MA, USA) was used to measure the midsole foam properties. A custom cylindrical head was used to load the rearfoot of the shoe at ~2000 N with a contact time of ~185 ms for 100

Figure 3.1.1: Footwear conditions VF_{intact} (high LBS) and VF_{cut} (low LBS)

cycles and the last 20 cycles were used to calculate energy return of the midsole (Hoogkamer et al., 2018). In flexion, mechanical testing resulted in bending stiffness measurements of 23.1 Nm/rad and 7.7 Nm/rad for VF_{intact} and VF_{cut}, respectively. Vertical compression energy return was 86% in both the VF_{intact} and VF_{cut} (Table 3.1.1).

	VF_{intact}	VF_{cut}
LBS in flexion (Nm/rad)	11.1	3.1
Energy return	86%	86%

Table 3.1.1: LBS and energy return measurements between footwear conditions
Cutting through the midsole and embedded carbon-fiber plate of a Vaporfly shoe effectively decreased its longitudinal bending stiffness (LBS), mechanically tested in flexion.
Material testing of the midsole at the rearfoot indicated that the energy return between the cut and intact shoes were the same.

3.2 EXPERIMENTAL PROTOCOL

We performed an a-priori sample size calculation (G*Power 3.1, Universität Kiel, Germany) for an ANOVA, repeated measures, within factors statistical test with input parameters of $\alpha = 0.05$, power = 0.8, number of factors = 3 (slope, speed, and LBS), and number of measurements = 2 (metabolic power in VF_{cut} vs VF_{intact}) (Table 3.2.1). Furthermore, we used data from previous work (Hoogkamer et al., 2018) to determine an appropriate effect size f = 0.17 and correlation among repeated measures = 0.96 (Table 3.2.1). With these inputs into G*Power, a sample size of 9 was suggested to be appropriate for this investigation (Table 3.2.1). To be able to use a counter-balanced study design with 6 potential incline orders (Table 3.4.2), we planned on recruiting 12 participants.

(inputs) (output)

Effect size f	α err prob	Power (1-β err prob)	Number of groups	Number of measurements	Corr among rep measures	**Sample size**
0.17	0.05	0.8	3	2	0.96	**9**

Table 3.2.1: A-priori sample size calculation
Input parameters (effect size f, α, power, number of groups, number of measurements, and correlation among repeated measures) to determine an a-priori sample size calculation using an ANOVA, repeated measures, within factors statistical test (G*Power 3.1, Universität Kiel, Germany).

To be eligible for recruitment, participants had to be between the ages of 18-45 years to participate, free of any orthopedic, cardiovascular, or neuromuscular conditions, and have not undergone any surgery or sustained an injury within 3 months prior to participation. The only footwear available were size US men's 9/9.5 and 10.5/11 (equivalent to size US women's 10.5/11 and 12/12.5) and participants needed to be able to fit these running shoes.

The experimental protocol of this study consisted of an energetics component and a biomechanics component. Data was collected across two visits to the Biomechanics Laboratory of Totman Gymnasium at University of Massachusetts Amherst. Participants arrived in a fasted state (i.e. no food or caffeine consumption at least 2 hours prior to the start of the running trials). After filling out and signing the PARQ and informed consent document, body mass and height were measured to allow for normalization of the oxygen consumption data.

Participants completed a standardized warm-up at a self-selected pace wearing their own shoes prior, followed by a standardized familiarization during which they ran at 4.44 m/s at a 0° incline for two minutes and 1.55 m/s at a 12° incline for another two minutes while breathing through the mouthpiece attached to the expired-gas analysis system and wearing standardized footwear (Puma Sutamina). Afterwards, extra time was provided for any additional stretching or warming up. Across two visits, participants completed a total of thirteen 5-minute running trials at various slopes and speeds on a force-measuring treadmill (Treadmetrix, Park City, UT). While participants ran, submaximal rates of oxygen uptake and carbon dioxide production were collected (True One 2400, Parvo Medics, Salt Lake City, UT). Simultaneously, their GRF data was recorded at 1200 Hz and motion capture (Oqus 3, Qualisys, Gothenburg, Sweden) data was collected at 240 Hz to measure the movement of the ankle and MTP joints. Retro-reflective markers were placed on the following locations of the right leg: toe tip, head of the first and fifth metatarsals, posterior aspect of the calcaneus, medial and lateral malleoli, medial and lateral femoral epicondyles, and lateral aspect of the shank (marker cluster consisting of four non-colinear markers mounted on a plastic plate). This study focused only on foot and ankle mechanics because Hoogkamer et al. did not find significant differences in biomechanical variables at the hip and knee when comparing the Vaporfly (prototype version) shoe with two other marathon racing shoes (Hoogkamer et al., 2019).

For each of the two footwear conditions, participants ran at three different inclines: 0, 6, and 12° (Roberts & Belliveau, 2005). The majority of uphill running studies have investigated relatively shallower slopes of ≤6° (~10.5%) (Vernillo et al., 2017). Therefore, to provide insights into the effect of footwear LBS during shallow uphill running, a slope of 6° was chosen, allowing for comparison with the current literature. Moreover, a slope of 12° (~21%) was also chosen to provide insights into the effect of footwear LBS at steeper inclines, allowing for contribution to the relatively minimal literature on steep uphill running. For ecological validity, a fixed metabolic power was used, rather than a fixed speed across inclines. Running speeds were determined with the following equation by Hoogkamer et al (Hoogkamer et al., 2014):

$$Net\ CoT\ (J/(kg \cdot m)) = 2.70 + 0.674 \cdot e^{-18.24\sin(\theta)} + \frac{g}{0.294} \cdot \sin(\theta)$$

Here, θ is the incline in degrees and g is the gravitational acceleration constant (9.81 m/s^2). By multiplying this equation with velocity (m/s), net CoT (J/(kg•m)) can be converted to metabolic power (W/kg). Therefore, setting the net metabolic power to 15 W/kg and the inclines to 0°, 6°, and 12° resulted in the running speeds of 4.44, 2.38, and 1.55 m/s, respectively. Based on this equation, the running conditions in the primary diagonal of the energetics experimental protocol (Table 3.3.1, Fast) should all yield a similar metabolic demand. The running conditions in the secondary diagonal (Table 3.3.1, Slow) were also included in the protocol to provide insight into the effects of incline at some given speed (and vice versa). The speed for the slow condition at the 12° incline was determined by again using the equation above with inputs of 15 W/kg and 18°. The speeds corresponding to each respective incline of the primary diagonal will be referred to as the fast-running conditions and those of the secondary diagonal will be referred to as the slow-running conditions. Using the Peronnet & Massicotte equation, metabolic power was calculated over the last two minutes of each running trial (Peronnet and Massicotte, 1991).

For the two visits of this study's protocol, the fast-running conditions (Table 3.3.1, Fast) were completed on one day and the slow-running conditions (Table 3.2.1, Slow) on another. With testing three incline angles, there were six possible incline orders (Table 3.3.2). To create a counter-balanced study design with a total of twelve possible orders, the original six randomizations were planned to be completed with the fast-running conditions on the first visit and the slow-running conditions on the second visit, and vice versa (Table 3.3.2). The order of the two footwear conditions was randomized but were completed consecutively for each incline- speed combination to limit the duration and variability of adjusting and readjusting the incline angle of the treadmill. Participants completed six running trials per visit, followed by a control running trial (0° at 4.44 m/s) to provide insights into between day differences in metabolic rate. Because this study investigated the effects of an increased LBS in running footwear (see above), the control running trial was completed in the VF_{cut} footwear condition.

		Incline		
		0°	6°	12°
Speed	1.15 m/s			Slow
	1.55 m/s		Slow	Fast
	2.38 m/s	Slow	Fast	
	4.44 m/s	Fast		

Table 3.3.1: Experimental protocol incline-speed running conditions
For the running energetics experimental protocol, the trials for each footwear condition consisted of running at 2.38 and 4.44 m/s at a 0° incline, 1.55 and 2.38 m/s at a 6° incline, and 1.15 and 1.55 m/s at a 12° incline. Fast represents running conditions included in the primary diagonal of the energetics protocol. Slow represents running conditions included in the secondary diagonal of the energetics protocol.

Recruiting 12 subjects would have been ideal, but because of a combination of the consequences of COVID-19 and a limited number of available runners capable of running at the appropriate pace for the experimental protocol, only 9 subjects were recruited. Moreover, although passing initial screening (capable of running a 5-km race in 18 minutes, or equivalent in another distance running event), two subjects were unable to complete the experimental protocol at a submaximal effort (indicated by an RER>1). There were also issues with the ground reaction force data for one subject. This left a sample size of 7 for the energetics analysis and a sample size of 6 for the biomechanics analysis. Therefore, with an underpowered study, it must be noted that there may be significant differences among the experimental outcomes that went undetected.

3.3 DATA PROCESSING AND ANALYSIS

Visual3D (C-motion, Germantown, MD) motion capture data analysis and modeling software was used to process all raw biomechanics data to determine ankle and MTP joint angles, angular velocities, moments, and powers. To determine joint work, the joint powers were integrated using custom MATLAB (MathWorks, Natick, MA) code.

3.3.1 Anthropometric Model

Visual3D was used to build a 6 degrees of freedom three-dimensional anthropometric model of a right lower leg for each participant. The model consisted of a shank, foot, and fore-foot segment. For the shank segment, the knee joint center defined the proximal end, and the ankle joint center defined the distal end. For the foot segment, the ankle joint center defined the proximal end, and the MTP joint center defined the distal end. For the fore-foot segment, the MTP joint center defined the proximal end, and the toe-tip defined the distal end. The knee joint center was defined as the midpoint between the medial and lateral femoral epicondyles. The ankle joint center was defined as the midpoint between the medial and lateral malleoli. The MTP joint center was defined as the midpoint between the first and fifth metatarsophalangeal heads.

3.3.2 Signal Processing

Motion capture data were visually inspected and gap-filled accordingly in Qualisys prior to analysis in Visual3d. Raw marker motion trajectory and ground reaction force data were filtered using a fourth-order low-pass Butterworth filter with a 14 Hz cut-off frequency. Foot-strike and toe-off were determined when the vertical GRF crossed a 20-N threshold level (default for Visual3D). Each running trial was also visually inspected to check the accuracy of these events. Any misplaced labels were manually removed or adjusted accordingly.

3.3.3 Method of Calculation

For the ankle and MTP joints, we calculated joint angles, angular velocities, moments, powers, and work. Three-dimensional kinematics of the ankle and MTP joints were calculated using an XYZ Cardan sequence (default for Visual3D), such that the x-axis represents lateral/medial, y-axis represent anterior/posterior, and z-axis represents up/down. Joint kinetics were calculated using an inverse dynamics approach through Visual3D. The moments calculated with Visual3D are internal moments. We defined the MTP moment and power to be zero until the resultant GRF vector originated distal to the MTP joint center. The local coordinate system was defined at the proximal joint center for each segment. Foot external rotation was calculated in Visual3D from the orientation of the foot segment (transverse plane) relative to the lab (global). Foot-strike angle was calculated as the global orientation of the foot (sagittal plane) upon initial contact on the treadmill subtracted by the global orientation of the foot during the static trials (level surface). To account for the angle of the running surface during the uphill running conditions, the calculated foot-strike angles were subtracted by 6 and 12 at the 6° and 12° inclines, respectively (i.e. foot-strike angle at 6° incline = orientation of foot upon ground contact – orientation of foot during static – 6). Positive foot-strike angles indicated heel-striking, and negative foot-strike angles indicated forefoot-striking. All calculated biomechanics data were normalized to 100% of stance and averaged across shoes within each participant.

3.3.4 Statistics

Using a three-way ANOVA with repeated measures, we compared metabolic power, contact time, step frequency, duty factor, and joint work while running in the two shoe conditions over two speed conditions at three inclines. Analyses were performed using SAS

OnDemand for Academics software (SAS, Cary, NC), with a traditional significance level (α=0.05). We also compared joint angles, angular velocities, moments, and powers using one-dimensional spatial parametric mapping (SPM) to conduct a three-way ANOVA with repeated measures. Analyses were performed using the MATLAB open-source software package spm1D (https://spm1d.org/), with a traditional significance level (α=0.05).

Randomizations	R1	*R2	*R3	*R4	R5	*R6	R7	*R8	R9	*R10	R11	R12
Speed 1 (Day 1)	Fast	Fast	Fast	Fast	Fast	Fast	Slow	Slow	Slow	Slow	Slow	Slow
Incline 1	0°	0°	6°	6°	12°	12°	0°	0°	6°	6°	12°	12°
Shoe 1	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact
Shoe 2	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut
Incline 2	6°	12°	12°	0°	0°	6°	6°	12°	12°	0°	0°	6°
Shoe 1	Cut	Cut	Intact	Cut	Intact	Intact	Cut	Cut	Intact	Cut	Intact	Intact
Shoe 2	Intact	Intact	Cut	Intact	Cut	Cut	Intact	Intact	Cut	Intact	Cut	Cut
Incline 3	12°	6°	0°	12°	6°	0°	12°	6°	0°	12°	6°	0°
Shoe 1	Cut	Cut	Cut	Intact	Intact	Intact	Cut	Cut	Cut	Intact	Intact	Intact
Shoe 2	Intact	Intact	Intact	Cut	Cut	Cut	Intact	Intact	Intact	Cut	Cut	Cut
Control	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s
Incline	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
Shoe	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut
Speed 2 (Day 2)	Slow	Slow	Slow	Slow	Slow	Slow	Fast	Fast	Fast	Fast	Fast	Fast
Incline 1	0°	0°	6°	6°	12°	12°	0°	0°	6°	6°	12°	12°
Shoe 1	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact
Shoe 2	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut	Intact	Cut
Incline 2	6°	12°	12°	0°	0°	6°	6°	12°	12°	0°	0°	6°
Shoe 1	Cut	Cut	Intact	Cut	Intact	Intact	Cut	Cut	Intact	Cut	Intact	Intact
Shoe 2	Intact	Intact	Cut	Intact	Cut	Cut	Intact	Intact	Cut	Intact	Cut	Cut
Incline 3	12°	6°	0°	12°	6°	0°	12°	6°	0°	12°	6°	0°
Shoe 1	Cut	Cut	Cut	Intact	Intact	Intact	Cut	Cut	Cut	Intact	Intact	Intact
Shoe 2	Intact	Intact	Intact	Cut	Cut	Cut	Intact	Intact	Intact	Cut	Cut	Cut
Control	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s	4.44 m/s
Incline	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
Shoe	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut	Cut

Table 3.3.2: Twelve possible variations of the experimental protocol
To investigate the three incline angles (0, 6, and 12°), there were six possible randomizations, but a total of twelve randomizations is ideal to achieve a counter-balanced study design.
*Randomizations of the experimental protocol with complete data that were used for the energetics and biomechanics analyses.

CHAPTER 4

RESULTS

A total of nine participants were recruited, but two participants were removed from the metabolic power analysis (n = 7) and three participants were removed from the biomechanics analysis (n = 6).

4.1 METABOLIC POWER

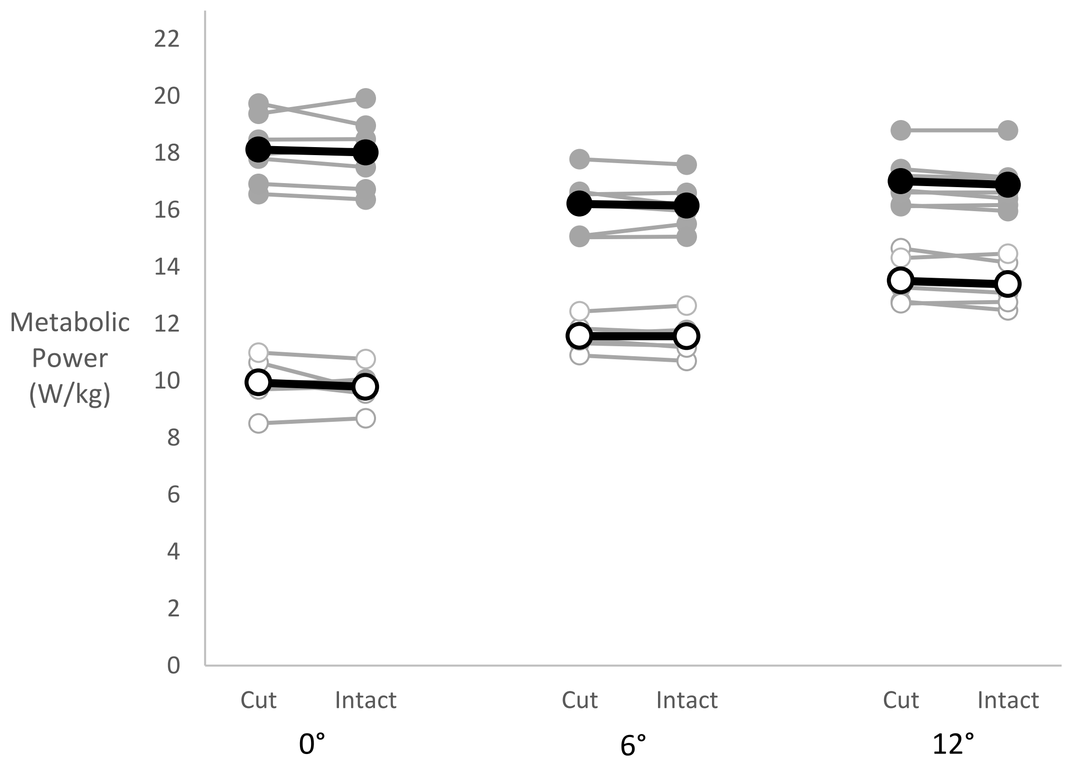

Figure 4.1.1: Metabolic power was similar between shoe conditions
Metabolic power (W/kg) in the cut and intact shoe conditions at each incline and their respective fast (filled circles) and slow (open circles) running speeds. At each incline-speed combination, there were no significant statistical differences between the metabolic powers running in the cut and intact shoes. Individual data (n=7) is shown in grey and the average is shown in black.

Overall, there was no significant main effect of shoe ($p = 0.3711$) on metabolic power, but there was a significant main effect of incline ($p < 0.0001$) and speed ($p < 0.0001$).

Specifically, metabolic power at the 12° incline was significantly ($p < 0.0001$) greater compared to at the 0° and 6° inclines. There was no significant difference between the metabolic power at the 0° and 6° inclines ($p = 0.7614$). Furthermore, the metabolic power at the slow speed was significantly ($p < 0.0001$) lower compared to the fast speed. A significant incline × speed interaction ($p < 0.0001$) was also observed, such that the metabolic power during level running at the fast speed was significantly greater compared to the 6° and 12° inclines while it was significantly lower at the slow speed, and the metabolic powers at the 6° incline for both speeds were significantly lower compared to the 12° incline. Importantly, the metabolic power during running between the cut and intact shoes were not significantly different at any incline (0°, 6°, and 12°) or speed (fast vs slow) (Figure 4.1).

4.2 SPATIOTEMPORAL PARAMETERS

4.2.1 CONTACT TIME

Overall, there was no significant main effect of shoe on contact time (Table 4.5.1). However, there was a significant main effect of incline on contact time ($p < 0.0001$). Contact time was significantly longer at the 12° incline compared to the 0° ($p < 0.0001$) and 6° ($p < 0.0001$) inclines, respectively. Contact time was also significantly longer at the 6° incline compared to the 0° incline ($p < 0.0001$). There was also a significant main effect of speed on contact time ($p < 0.0001$). Contact time was significantly shorter at the fast speed compared to the slow speed. There was no significant shoe × incline interaction or significant shoe × speed interaction on contact time. However, there was a significant incline × speed interaction ($p = 0.0065$), indicating that the reduction in contact time at the faster speed was less pronounced at the steeper inclines.

4.2.2 STEP FREQUENCY

Overall, there was no significant main effect of shoe on step frequency (Table 4.2.1). However, there was a significant main effect of incline on step frequency ($p < 0.0001$). Step frequency was significantly higher at the 0° incline compared to the 6° ($p < 0.0001$) and 12° ($p < 0.0001$) inclines, respectively. Step frequency was similar at the 6° incline compared to the 12° incline. There was also a significant main effect of speed on step frequency ($p < 0.0001$). Step frequency was significantly greater at the fast speed compared to the slow speed. Importantly, there was no significant shoe × incline interaction or significant shoe ×speed interaction on step frequency. However, there was a significant incline × speed interaction ($p = 0.0053$), indicating that the reduction in step frequency at the slower speed was less pronounced at the steeper inclines.

4.2.3 Duty Factor

Overall, there was no significant main effect of shoe on duty factor (Table 4.2.1). However, there was a significant main effect of incline on duty factor ($p < 0.0001$). Duty factor was significantly greater at the 12° incline compared to the 0° ($p < 0.0001$) and 6° ($p < 0.0001$) inclines, respectively. Duty factor was also significantly greater at the 12° incline compared to the 6° incline ($p < 0.0001$). There was also a significant main effect of speed on duty factor ($p < 0.0001$). Duty factor was significantly greater at the slow speed compared to the fast speed. In fact, at the slow speed, specifically in the uphill conditions, duty factor approached 50%. There was no significant shoe × incline interaction or significant shoe ×speed interaction on duty factor. However, there was a significant incline × speed interaction ($p = 0.0003$), indicating that the increase in duty factor at the slower speed was less pronounced at the steeper inclines.

		0°		6°		12°	
		Cut	***Intact***	***Cut***	***Intact***	***Cut***	***Intact***
Contact Time (seconds)	*Fast*	0.196 ± 0.015	0.199 ± 0.014	0.278 ± 0.017$^{\#}$	0.278 ± 0.012$^{\#}$	0.326 ± 0.039$^{\#+}$	0.331 ± 0.035$^{\#+}$
	Slow	*0.269 ± 0.022*	*0.273 ± 0.021*	*0.328 ± 0.042*$^{\#}$	*0.342 ± 0.042*$^{\#}$	*0.357 ± 0.036*$^{\#+}$	*0.371 ± 0.034*$^{\#+}$
Step Frequency (steps/second)	*Fast*	3.02 ± 0.10	3.02 ± 0.11	2.84 ± 0.13$^{\#}$	2.86 ± 0.14$^{\#}$	2.81 ± 0.12$^{\#}$	2.81 ± 0.12$^{\#}$
	Slow	*2.74 ± 0.16*	*2.77 ± 0.15*	*2.73 ± 0.12*$^{\#}$	*2.70 ± 0.13*$^{\#}$	*2.66 ± 0.14*$^{\#}$	*2.67 ± 0.15*$^{\#}$
Duty Factor (%)	*Fast*	29.7 ± 2.8	30.0 ± 2.6	39.4 ± 2.4$^{\#}$	39.7 ± 2.2$^{\#}$	45.7 ± 4.4$^{\#+}$	46.5 ± 4.0$^{\#+}$
	Slow	*36.9 ± 3.5*	*37.7 ± 3.1*	*44.6 ± 5.0*$^{\#}$	*46.1 ± 4.9*$^{\#}$	*47.3 ± 3.9*$^{\#+}$	*49.4 ± 3.5*$^{\#+}$

Table 4.2.1: Contact time, step frequency, and duty factor were similar between shoe conditions
At each incline-speed combination, there were no significant statistical differences between the cut and intact shoes for contact time, step frequency, and duty factor.
There was a significant main effect of incline for contact time, step frequency, and duty factor, where # indicates a significant difference compared to 0°, and #+ indicates a significant difference compared to 6°.
There was also a significant main effect of speed for contact time, step frequency, and duty factor, where *italics* indicates a significant difference compared to the fast-running speed.

4.3 FOOT-STRIKE ANGLE

		Foot-strike Angle (degrees)		
Speed	Shoe	**0°**	**6° #**	**12° #+**
Fast	**Cut**	10.4 ± 10.1	-0.31 ± 4.53	-10.2 ± 7.51
	Intact	8.84 ± 10.3	-1.09 ± 4.65	-10.4 ± 9.06
Slow	**Cut**	4.42 ± 8.34	-1.58 ± 4.31	-11.4 ± 7.29
	Intact	4.74 ± 9.72	-1.94 ± 5.53	-9.91 ± 7.31

Table 4.3.1: Comparison of foot-strike angle between the cut and intact shoes at each incline and their respective fast and slow running speeds.
There was no significant main effect of shoe on foot-strike angle.
There was a significant main effect of incline where # indicates a significant difference compared to level and + indicates a significant difference compared to the 6° incline.
There was no significant main effect of speed on foot-strike angle.
There were also no significant interactions.

Group average data for each experimental condition is shown in Table 4.3.1. Overall, there was no significant main effect of shoe on foot-strike angle (Figure 4.3.1). However, there was a significant main effect of incline ($p < 0.0001$). Specifically, foot-strike angle decreased as incline increased, indicating subjects adopted more of a forefoot-strike running pattern. Compared to level running, foot-strike angle was significantly lower at the 6° ($p < 0.0001$) and 12° ($p < 0.0001$) inclines. Compared to the 6° incline, foot-strike angle was significantly lower at the 12° incline ($p < 0.0001$). There was also no significant main effect of speed on foot-strike. Moreover, there was no significant shoe × incline interaction, shoe × speed interaction, or incline × speed interaction on foot-strike angle.

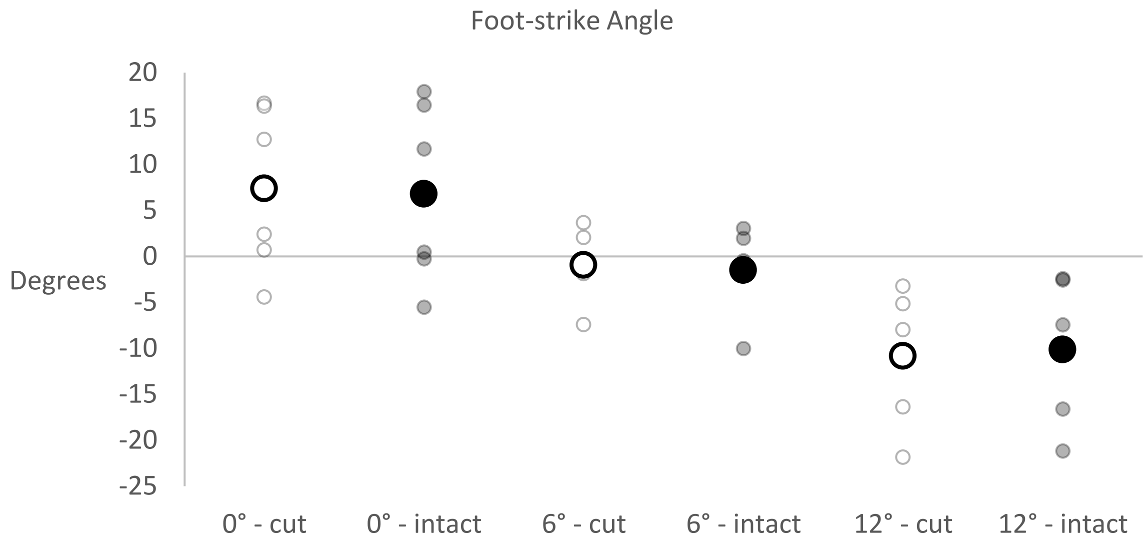

Figure 4.3.1: Foot-strike angle decreased as incline increased.
On average (of both speeds), foot-strike angle was similar between the cut (open circles) and intact (filled circles) shoes.
Foot-strike angle significantly decreased as incline increased across all inclines, indicating adoption of a forefoot-strike gait.
Averages shown in black and individual data shown in grey.

4.4 ANKLE MECHANICS

In the VF_{intact} shoes, there was a reduction in ankle angular velocity. Ankle angle, moment, and power were similar between the VF_{cut} and VF_{intact} shoes. Ankle angle was not independent of incline.

4.4.1 ANKLE ANGLE

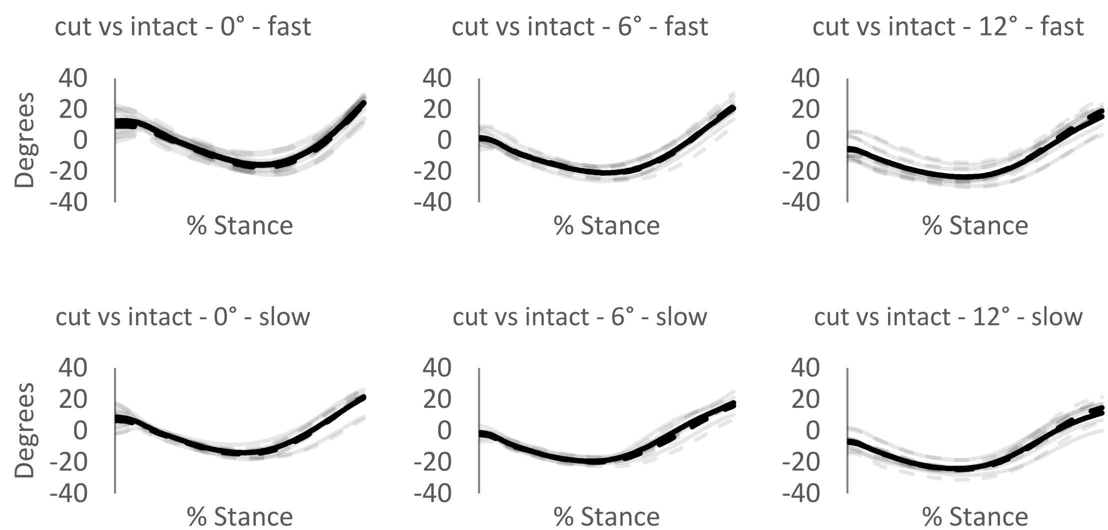

Figure 4.4.1: Ankle angle during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: Ankle angle (°) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: Ankle angle (°) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.4.1. Overall, there was no significant main effect of shoe on ankle angle (Figure 4.4.2). However, there was a significant main effect of incline on ankle angle. Specifically, ankle angles were more dorsiflexed as incline increased during 0-59% of stance ($p < 0.001$) and less plantarflexed as incline increased during 94-100% of stance ($p = 0.048$). There was also no significant main effect of speed on ankle angle. Importantly, there was a significant shoe × incline interaction during 85-100% of stance ($p = 0.036$), indicating that the ankle angle was more plantarflexed in the cut shoes than the intact shoes at the steepest incline (12°). There was also no significant shoe × speed interaction or incline × speed interaction on ankle angle.

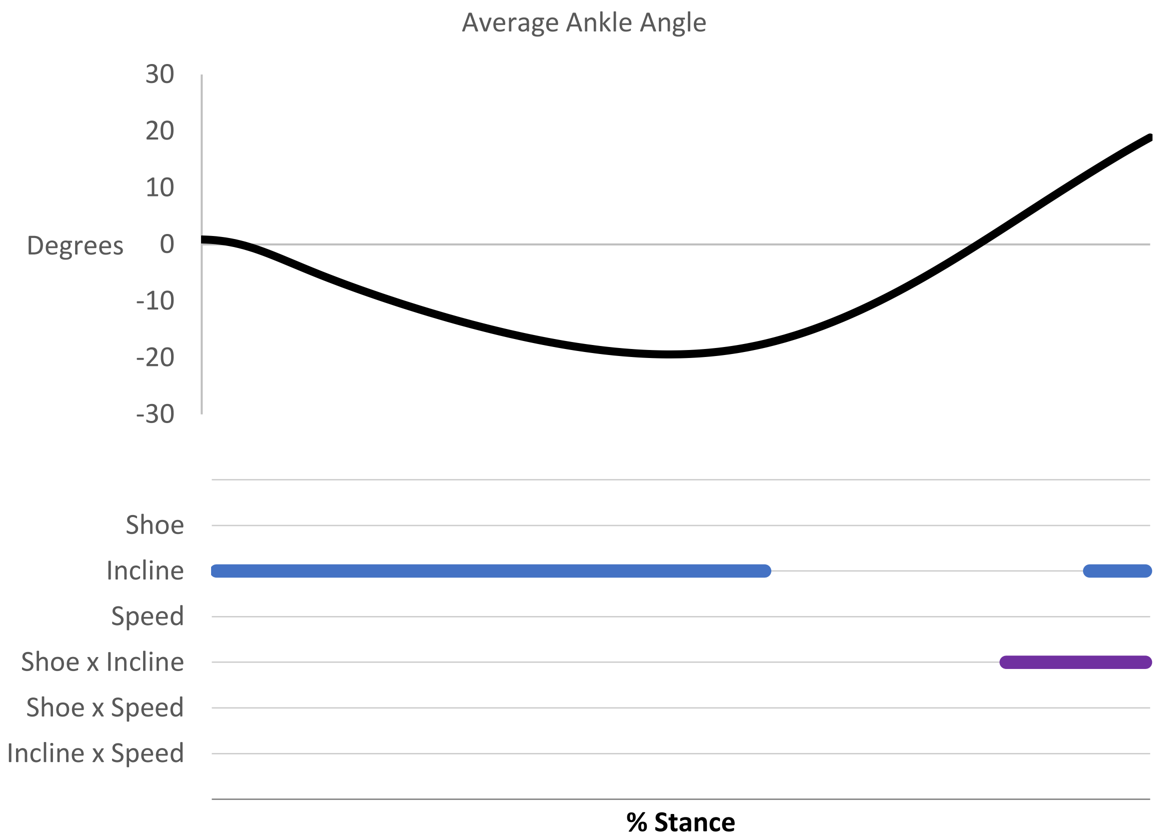

Figure 4.4.2A: Between shoe differences in late stance ankle angle became apparent at the steepest incline
(Top) Average ankle angle across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and shoe conditions (cut and intact).
(Bottom) Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and shoe during stance.

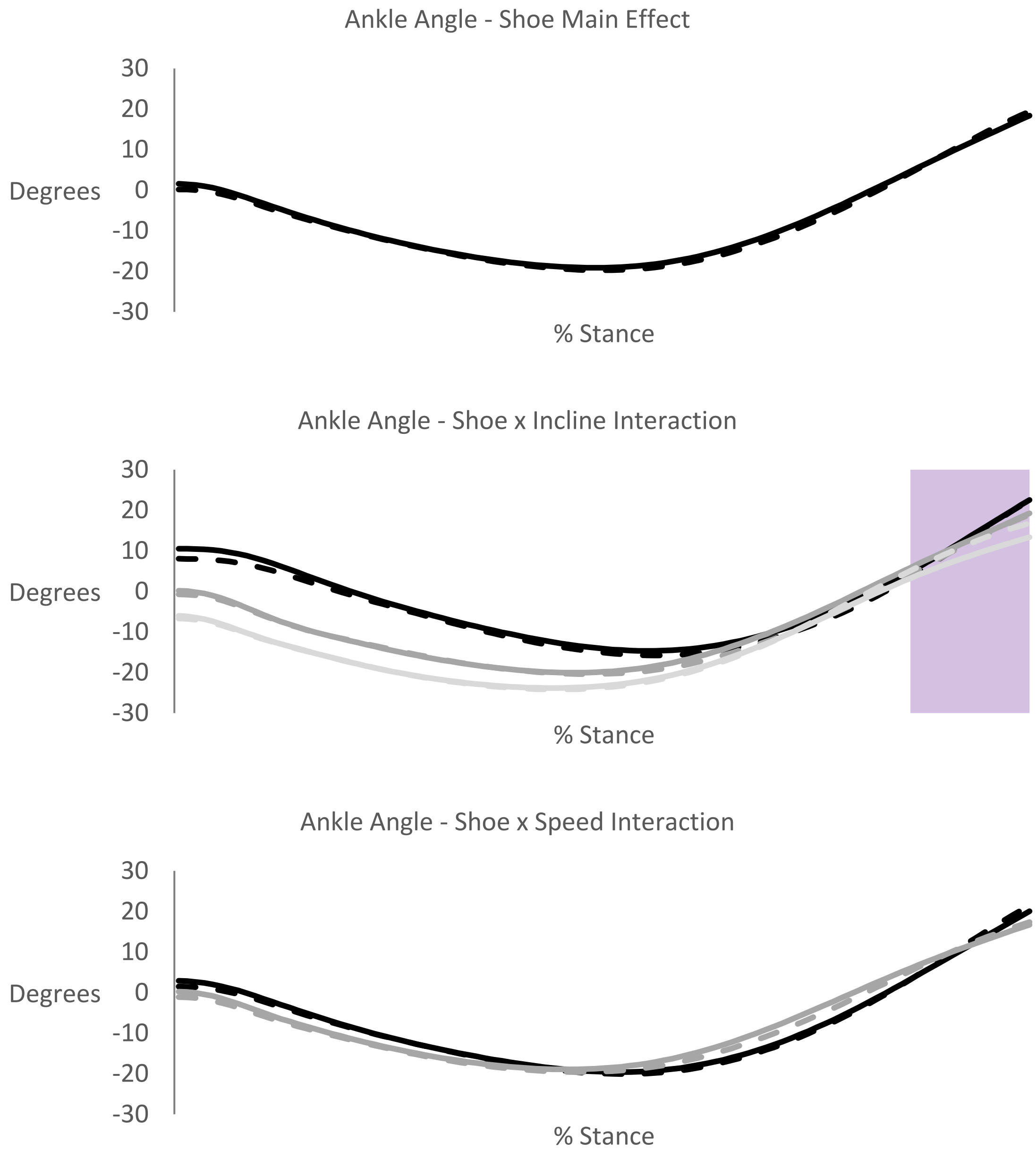

Figure 4.4.2B: Between shoe differences in late stance ankle angle became apparent at the steepest incline

(Top) Average ankle angle between the cut (dashed line) and intact (solid line) shoe conditions during stance. There was no significant main effect of shoe on ankle angle during stance.
(Middle) Average ankle angle at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was a significant shoe x incline interaction on ankle angle during 85-100% of stance ($p=0.036$).
(Bottom) Average ankle angle at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on ankle angle during stance.

4.4.2 ANKLE ANGULAR VELOCITY

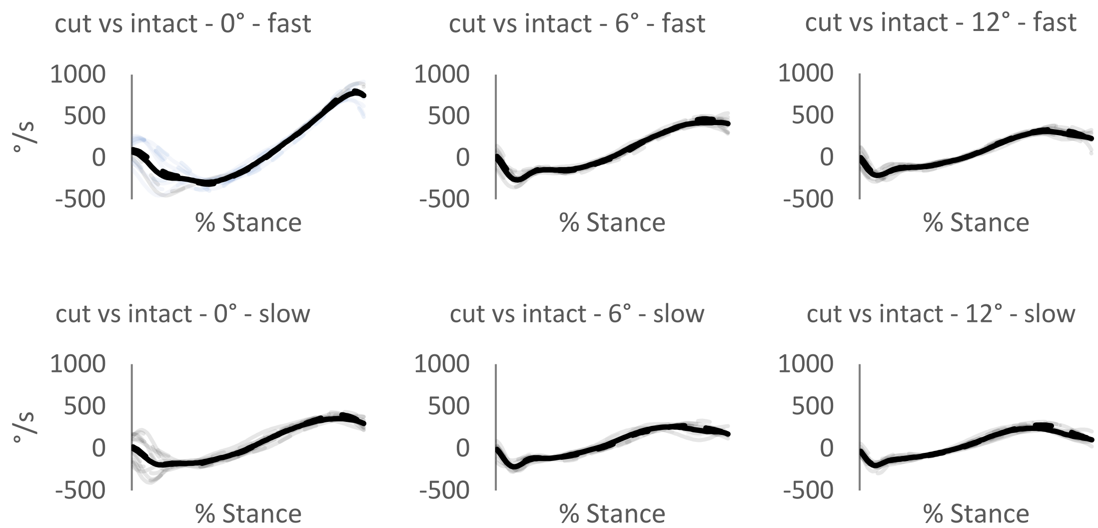

Figure 4.4.3: Ankle angular velocity during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: Ankle angular velocity (°/s) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: Ankle angular velocity (°/s) running conditions during % stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.4.3. Overall, there was a significant main effect of shoe on ankle angular velocity (Figure 4.4.4). Compared to the cut shoe, ankle angular velocities were significantly slower with the intact shoe during 14-16% ($p = 0.041$), faster during 29-35% ($p = 0.005$), and faster during 74-75% ($p = 0.0480$) of stance. There was also a significant main effect of incline. As incline increased, ankle angular velocities were significantly slower during 19-64% ($p < 0.001$) and 75-100% ($p < 0.001$) of stance. There was a significant main effect of speed as well. Compared to the slow-running condition, ankle angular velocities were significantly faster at the fast-running condition during 23-52% ($p < 0.001$) and 70-100% ($p < 0.001$) of stance. There was no significant shoe × incline interaction or shoe × speed interaction on ankle angular velocity. However, there was a significant incline x speed interaction during 29-55%

(p < 0.001) and 83-100% (p < 0.001) of stance, indicating ankle angular velocities were slower as incline increased and running speed decreased.

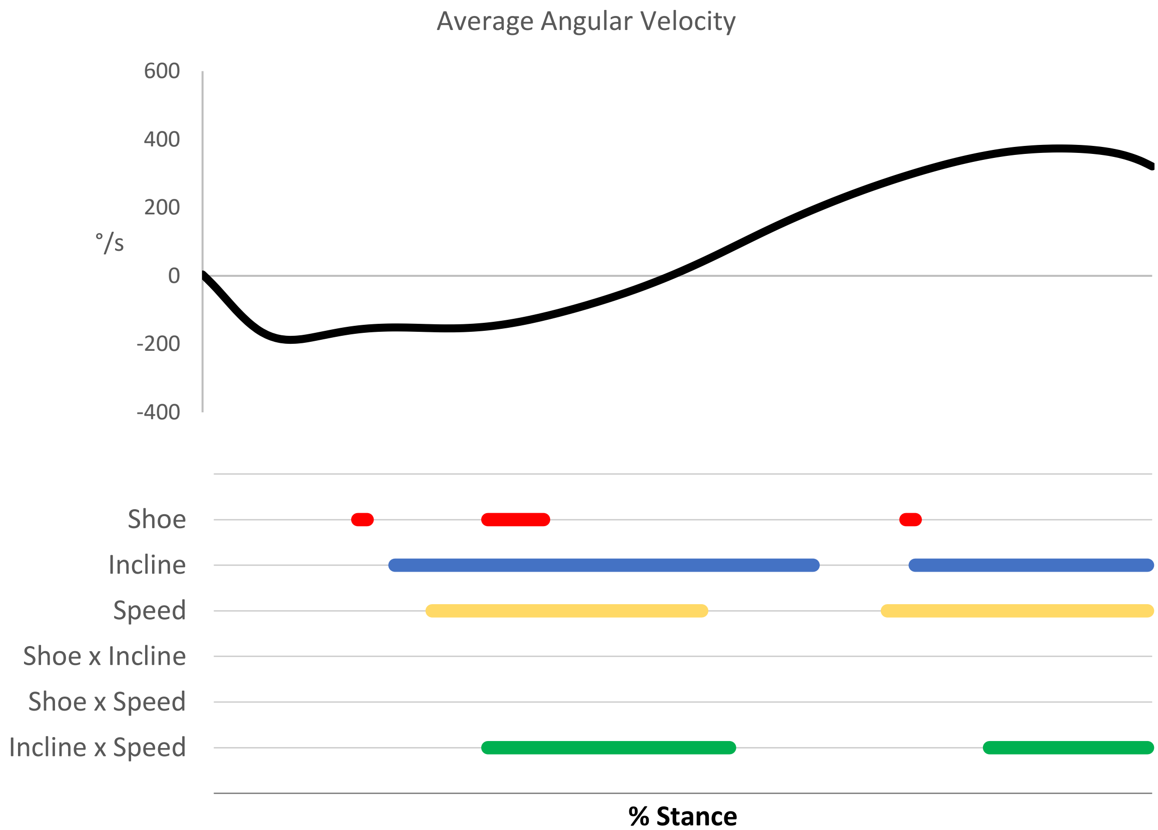

Figure 4.4.4A: Ankle angular velocity was slower with the intact shoes
(Top) Average ankle angular velocity across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

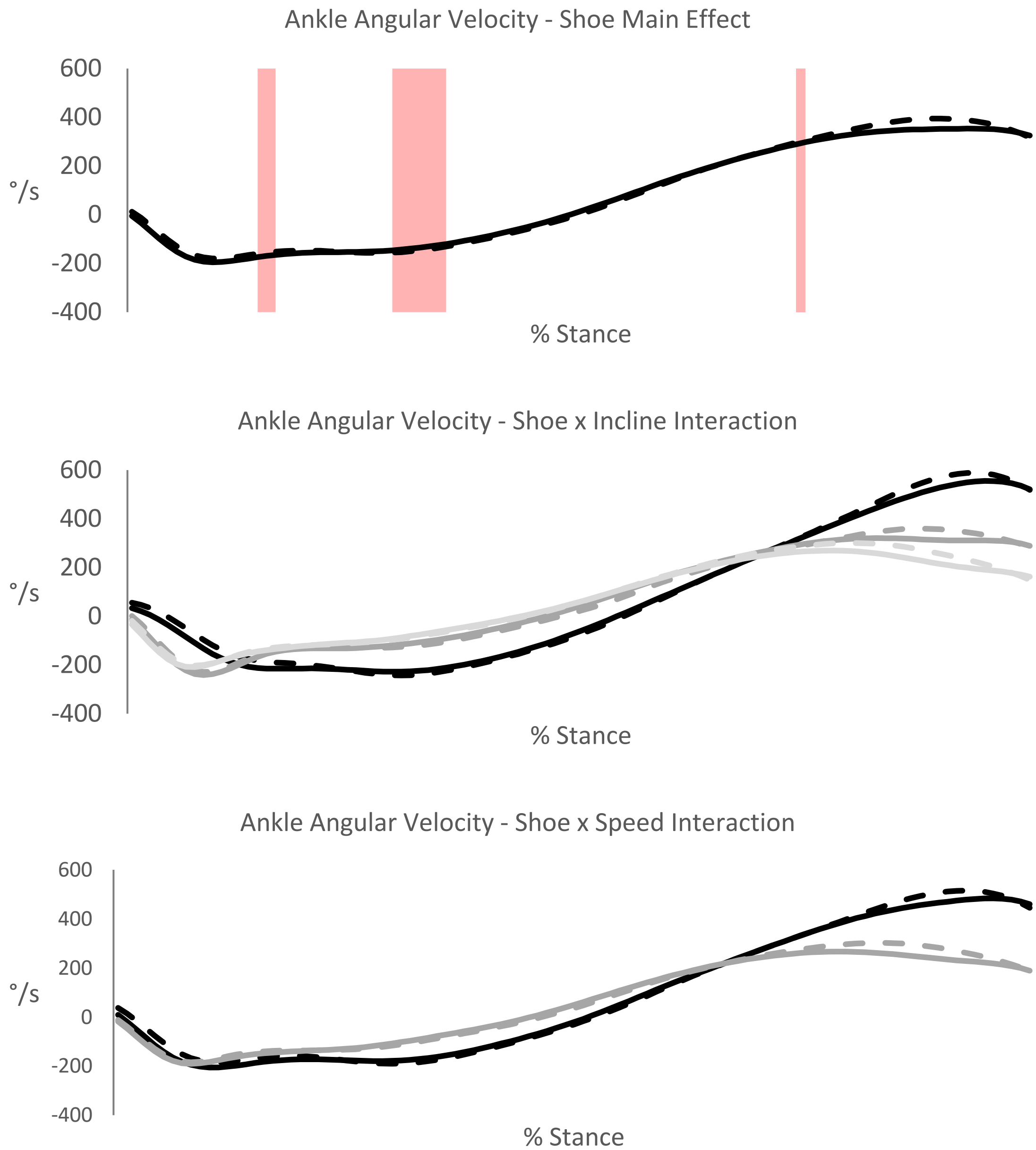

Figure 4.4.4B: Ankle angular velocity was slower with the intact shoes
(Top) Average ankle angular velocity between the cut (dashed line) and intact (solid) shoe conditions during stance. There was a significant main effect of shoe on ankle angular velocity during 15-16% (p=0.041), 29-35% (p=0.005), and 74-75% (p=0.048) of stance.
(Middle) Average ankle angular velocity at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was no significant shoe x incline interaction on ankle angular velocity during stance.
(Bottom) Average ankle angular velocity at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on ankle angular velocity during stance.

4.4.3 ANKLE MOMENT

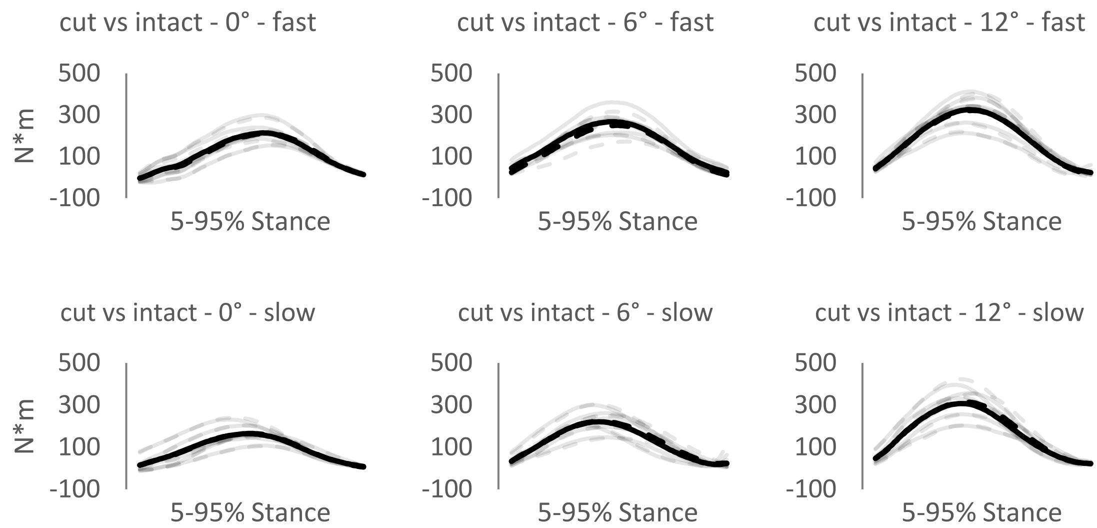

Figure 4.4.5: Ankle moment during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: Ankle moment (N*m) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: Ankle moment (N*m) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group Average data for each experimental condition is shown in Figure 4.4.5. Overall, there was no significant main effect of shoe on ankle moment (Figure 4.4.6). However, there was a significant main effect of incline on ankle moment. Specifically, ankle moment increased as incline increased during 5-68% of stance ($p < 0.001$). There was also no significant main effect of speed on ankle moment. There was no significant shoe × incline interaction, shoe × speed interaction, or incline × speed interaction on ankle moment.

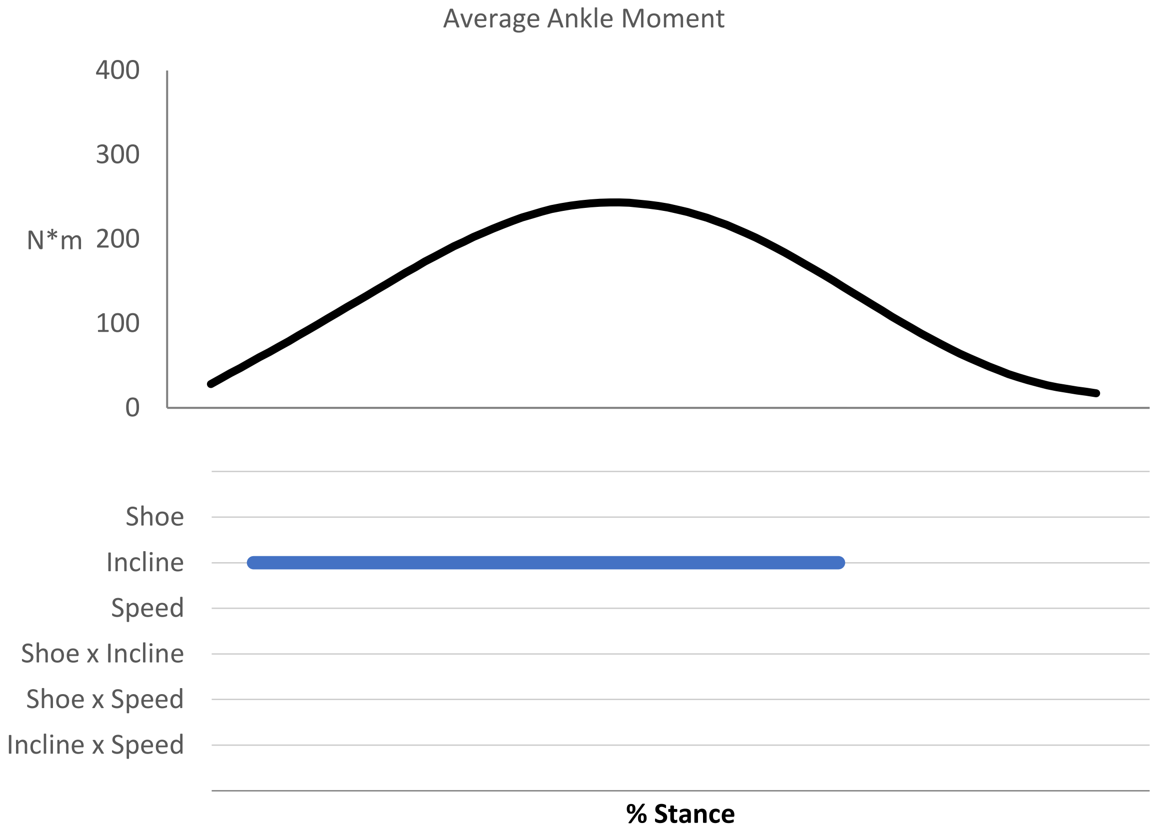

Figure 4.4.6A: MTP moments were similar between shoe conditions
(Top) Average MTP moment across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

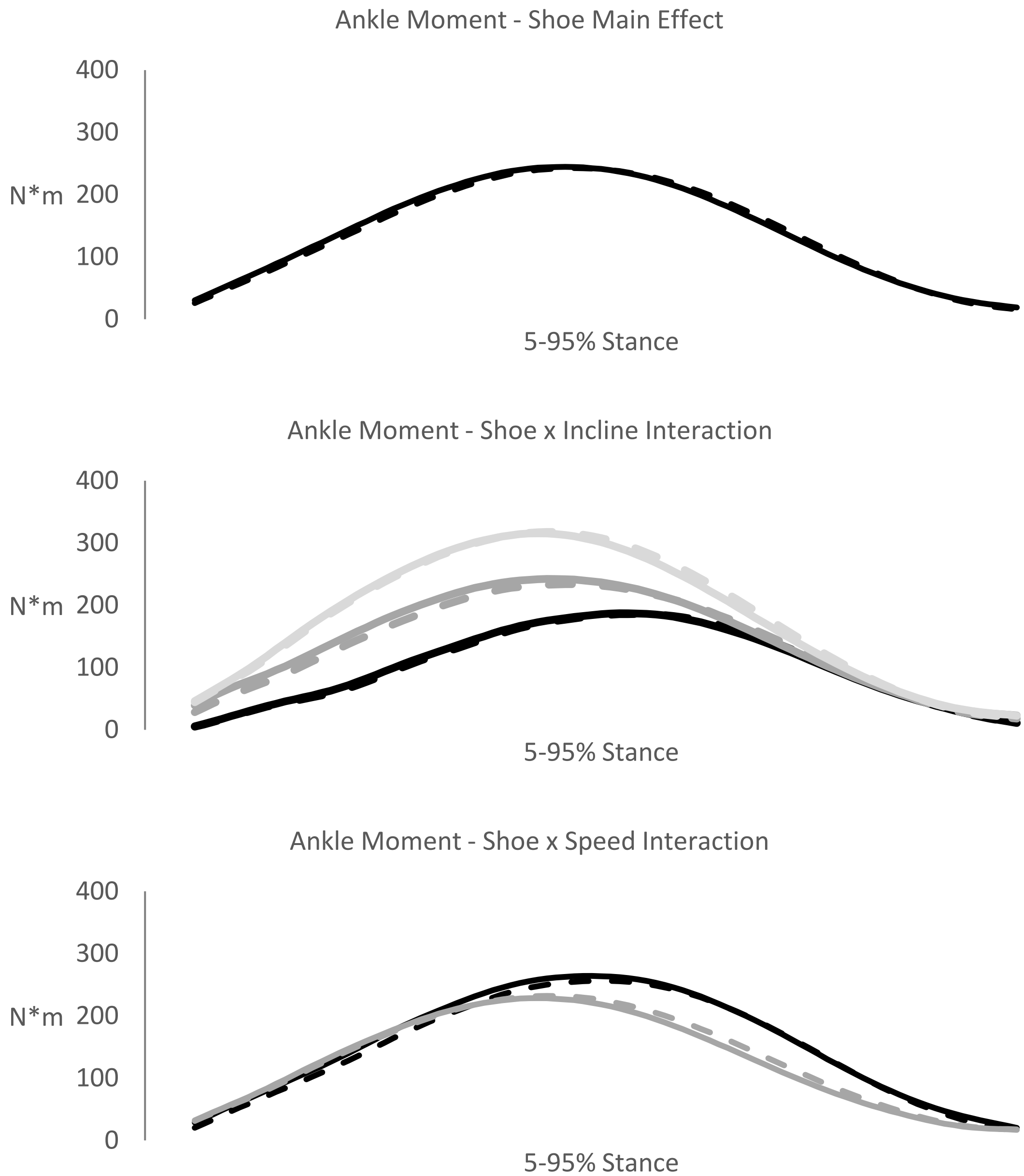

Figure 4.4.6B: MTP moments were similar between shoe conditions
(Top) Average MTP moment between the cut (dashed line) and intact (solid line) shoe conditions during stance. There was no significant main effect of shoe on MTP moment during stance.
(Middle) Average MTP moment at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was no significant shoe x incline interaction on MTP moment during stance.
(Bottom) Average MTP moment at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on MTP moment during stance.

4.4.4 Ankle Power

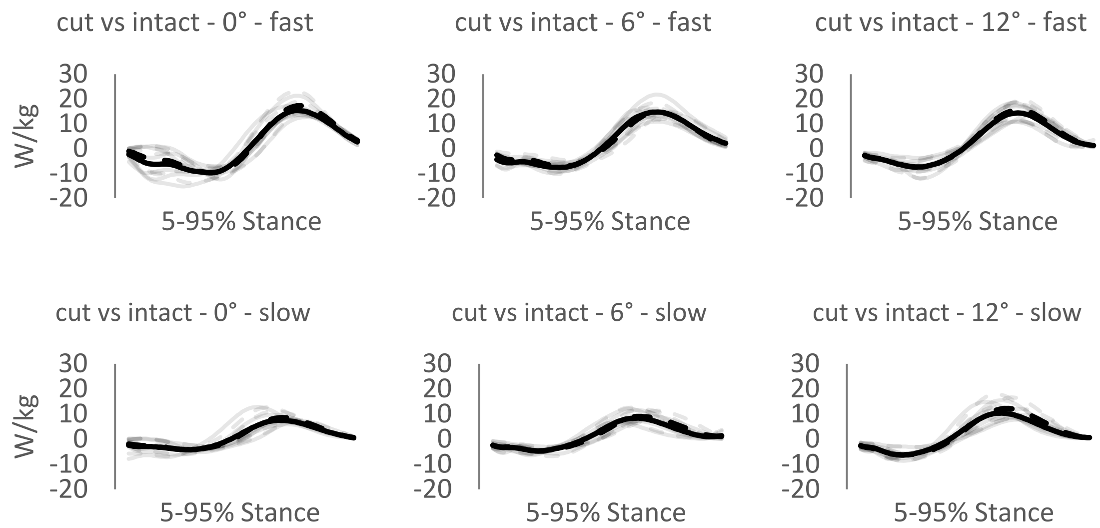

Figure 4.4.7: Ankle power during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: Ankle power (W/kg) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: Ankle power (W/kg) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.4.7. Overall, there was no significant main effect of shoe on ankle power (figure 4.4.8). However, there was a significant main effect of incline on ankle power. As incline increased, ankle power significantly increased during 33-62% during stance ($p < 0.001$) and decreased during 77-94% of stance ($p < 0.001$). There was also a significant main effect of speed on ankle power. Compared to the slow-running condition, ankle power was significantly greater at the fast-running condition during 77-93% of stance ($p < 0.001$). Moreover, there was no significant shoe × incline interaction on ankle power. There was a significant shoe × speed interaction during 5-7% of stance ($p = 0.039$), indicating that the ankle power was more negative in the cut shoes than in the intact shoes at the fast-running condition. There was also a significant incline × speed interaction during 34-50% ($p < 0.001$) and 73-94% ($p < 0.001$) of stance, indicating that the reduced ankle power at the faster speed was less pronounced at the steeper inclines.

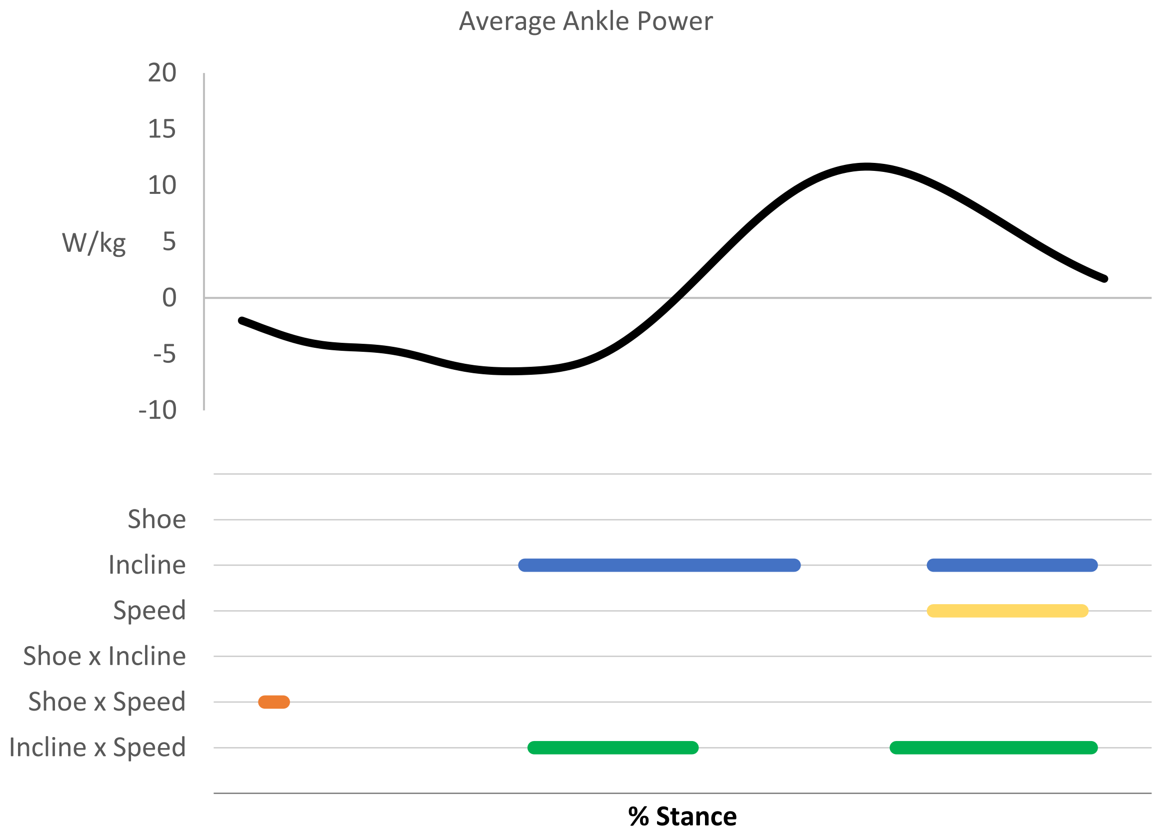

Figure 4.4.8A: Between shoe differences at foot-strike became apparent at the fast speeds (Top) Average ankle power across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

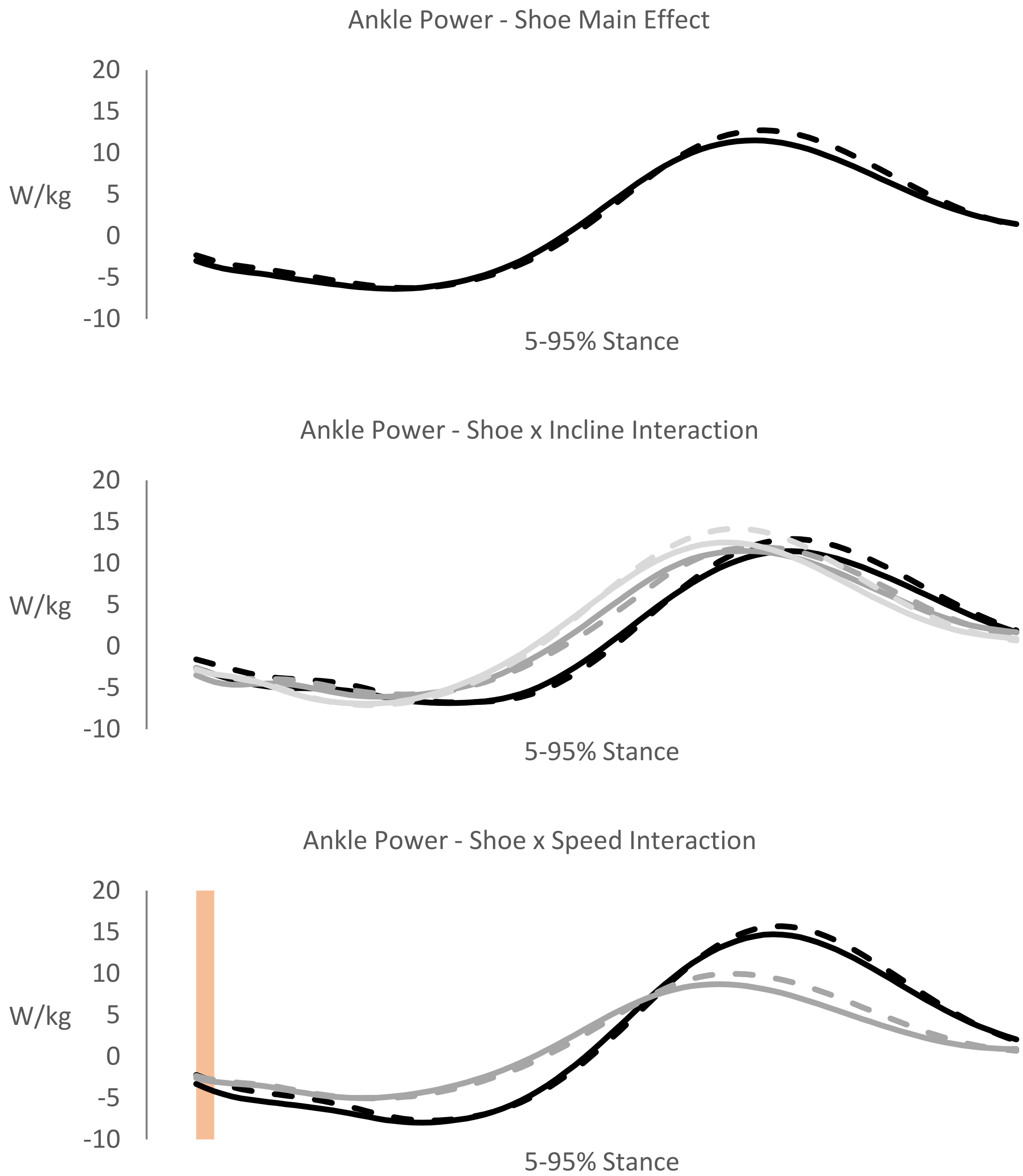

Figure 4.4.8B: Between shoe differences at foot-strike became apparent at the fast speeds
(Top) Average ankle power between the cut (dashed line) and intact (solid line) shoe conditions during stance. There was no significant main effect of shoe on ankle power during stance.
(Middle) Average ankle power at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was no significant shoe x incline interaction on ankle power during stance.
(Bottom) Average ankle power at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was a significant shoe x speed interaction on ankle power during 5-7% of stance ($p=0.039$)

4.5 MTP MECHANICS

In the VF_{intact} shoes, there was a reduction in MTP angle, angular velocity, and power. MTP moment was similar between the VF_{cut} and VF_{intact} shoes. The main effect of shoe on MTP power was independent of incline, and joint angle and angular velocity were not.

4.5.1 MTP ANGLE

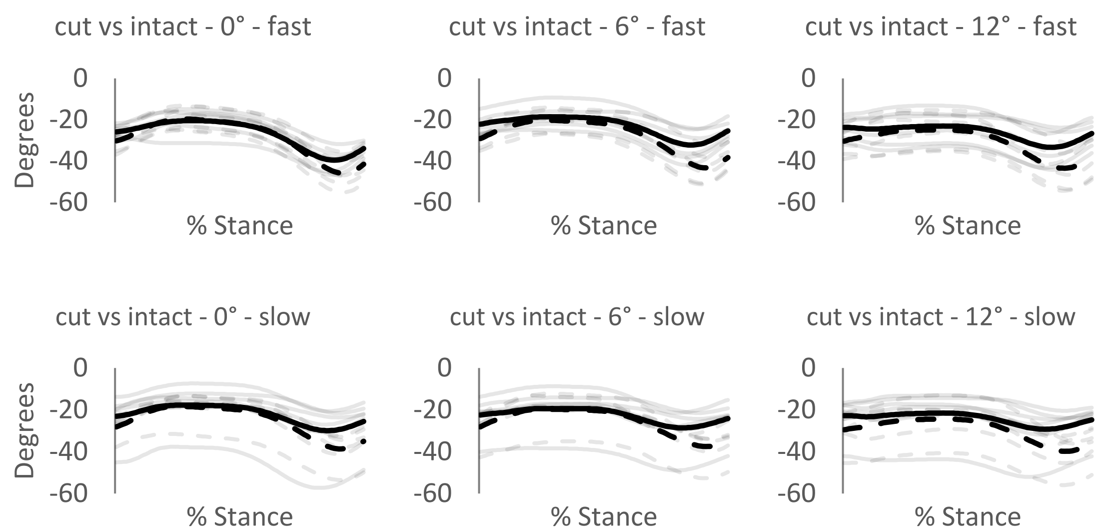

Figure 4.5.1: MTP angle during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: MTP angle (°) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: MTP angle (°) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.5.1. Overall, there was a significant main effect of shoe on MTP angle (Figure 4.5.2). Compared to the cut shoe, MTP angles were significantly less dorsiflexed with the intact shoe during 0-6% ($p = 0.047$) and 74-100% ($p = 0.020$) of stance. There was also a significant main effect of incline on MTP angle. As incline increased, MTP angles were more dorsiflexed during 18-62% ($p = 0.007$) and 83-100% ($p = 0.039$) of stance. However, there was no significant main effect of speed on MTP angle. There was a significant shoe × incline interaction during 73-90% of stance (p = 0.037), indicating that the reduced dorsiflexion angle in the intact shoes was more pronounced at the steeper inclines. There was no significant shoe × speed interaction or incline × speed interaction on MTP angle.

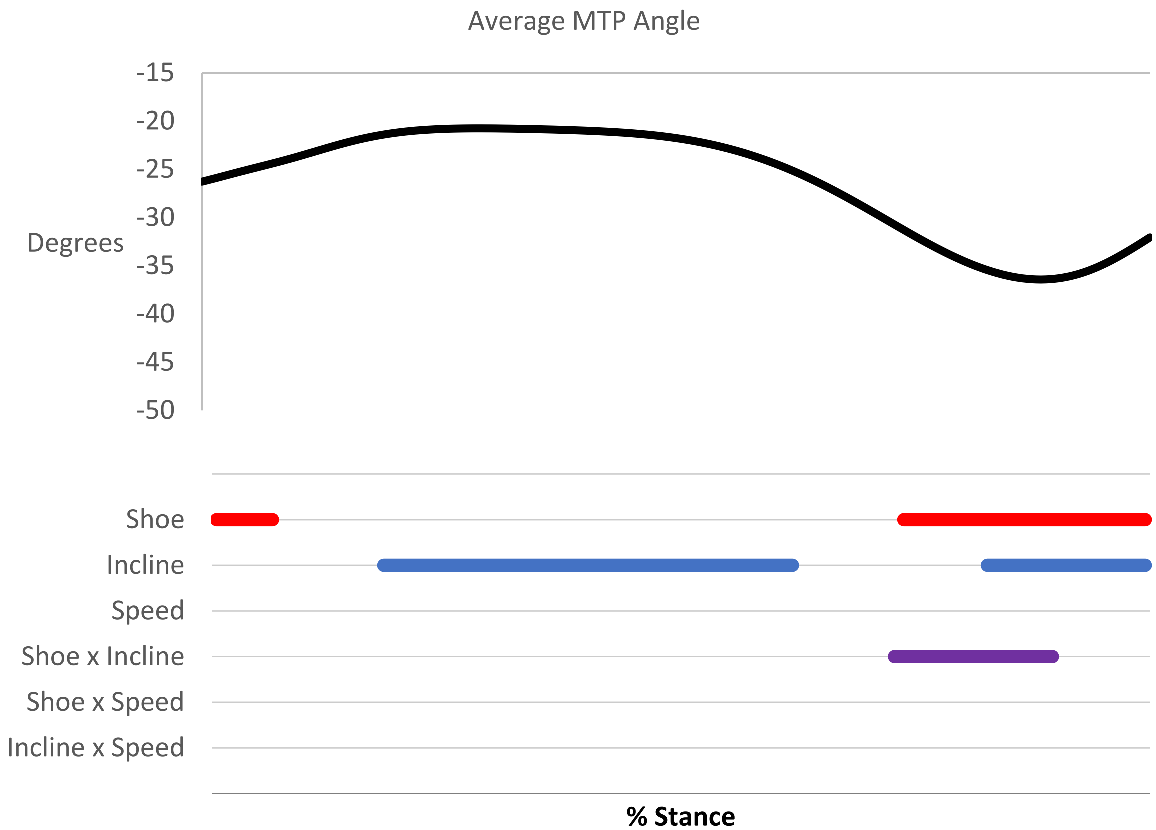

Figure 4.5.2A: MTP angle was less dorsiflexed with the intact shoes during foot-strike and toe-off
(Top) Average MTP angle across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

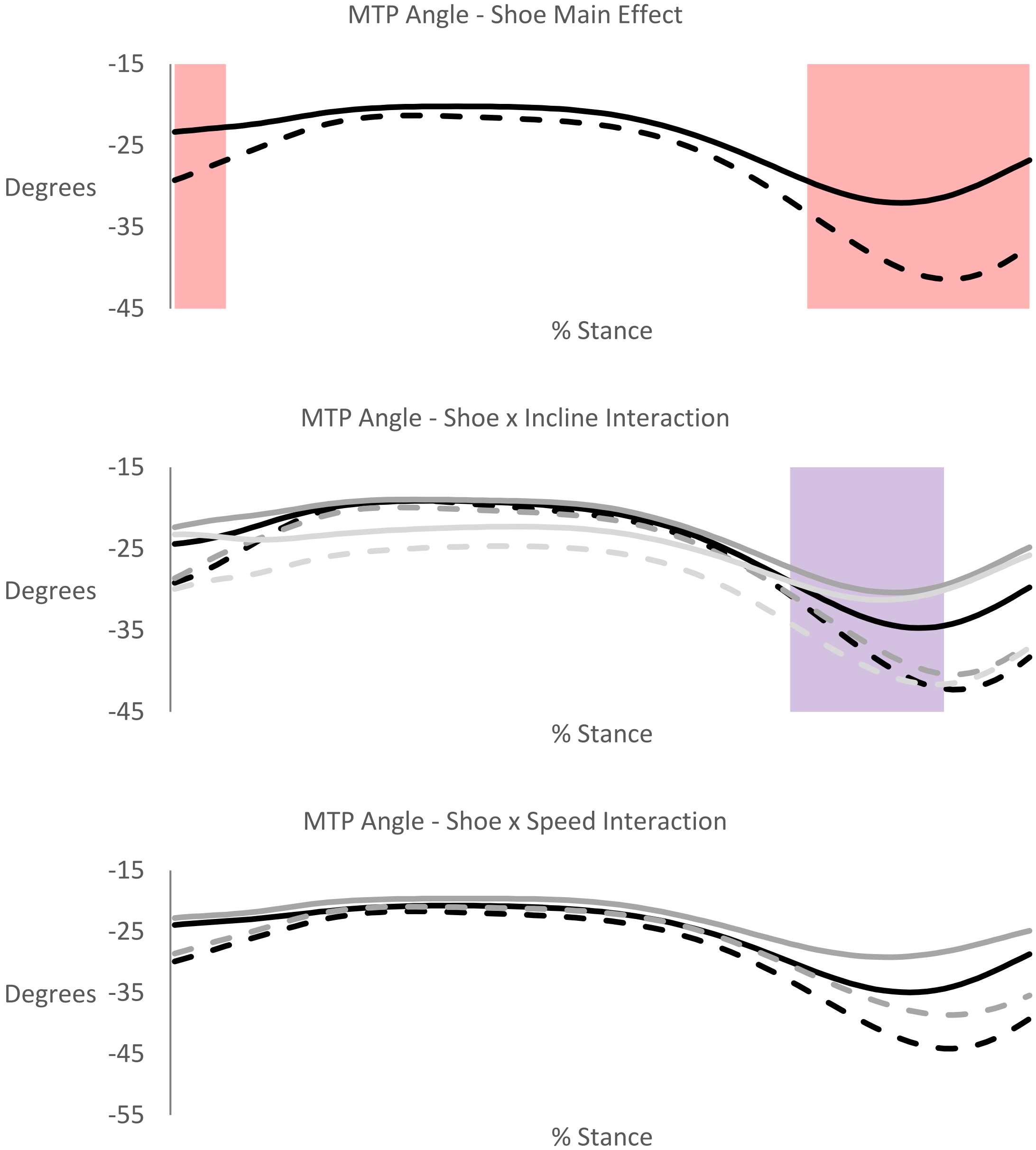

Figure 4.5.2B: MTP angle was less dorsiflexed with the intact shoes during foot-strike and toe-off
(Top) Average MTP angle between the cut (dashed line) and intact (solids line) shoe conditions during stance. There was a significant main effect of shoe on MTP angle during 0-6% ($p=0.047$) and 74-100% ($p=0.020$) of stance.
(Middle) Average MTP angle at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was a significant shoe x incline interaction on MTP angle during 73-90% of stance ($p=0.037$).
(Bottom) Average MTP angle at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on MTP angle during stance.

4.5.2 MTP Angular Velocity

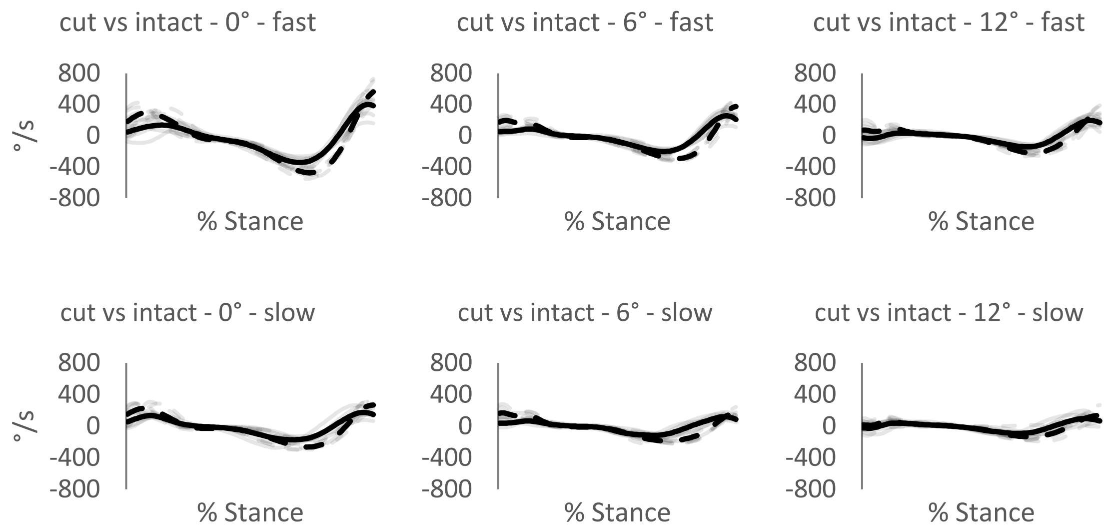

Figure 4.5.3: MTP angular velocity during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: MTP angular velocity (°/s) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: MTP angular velocity (°/s) of running conditions during % stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.5.3. Overall, there was a significant main effect of shoe on MTP angular velocity (Figure 4.5.4). Compared to the cut shoe, MTP angular velocities were significantly slower with the intact shoe during 0-9% ($p < 0.001$), 66-86% ($p < 0.001$), and 96-100% ($p = 0.030$) of stance. There was also a significant main effect of incline. As incline increased, MTP angular velocities were significantly slower during 3-16% ($p < 0.001$), 32-43% ($p < 0.001$), 55-86% ($p < 0.001$), and 92-100% ($p < 0.001$) of stance. There was a significant main effect of speed as well. Compared to the slow-running condition, MTP angular velocities were significantly faster at the fast-running condition during 56-81% ($p < 0.001$) and 95-100% ($p = 0.010$) of stance. Moreover, there was a significant shoe × incline interaction during 29-31% of stance ($p = 0.044$), indicating that the difference between shoes was smaller at the steep incline than during level running. Specifically, during this brief period, MTP dorsiflexion velocity was about 25°/s slower in the intact shoe than the cut shoe for level running, while it was similar at the 12° incline. There was also a significant incline × speed interaction during 18-21% ($p = 0.036$) and 37-72% ($p < 0.001$) of stance, indicating that the reduced MTP angular velocities at the faster speed is less pronounced at the steeper inclines. Furthermore, there was no significant shoe × speed interaction on MTP angular velocity.

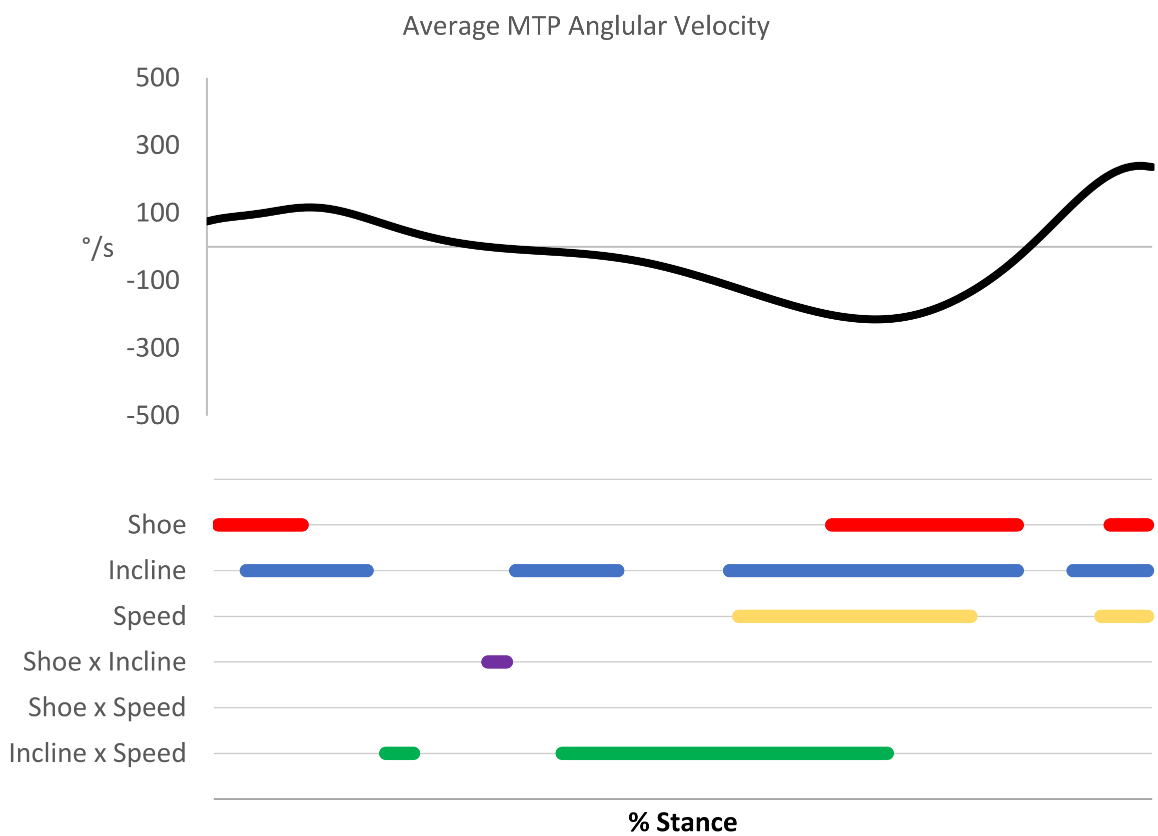

Figure 4.5.4A: MTP angular velocity was slower with the intact shoes
(Top) Average MTP angular velocity across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

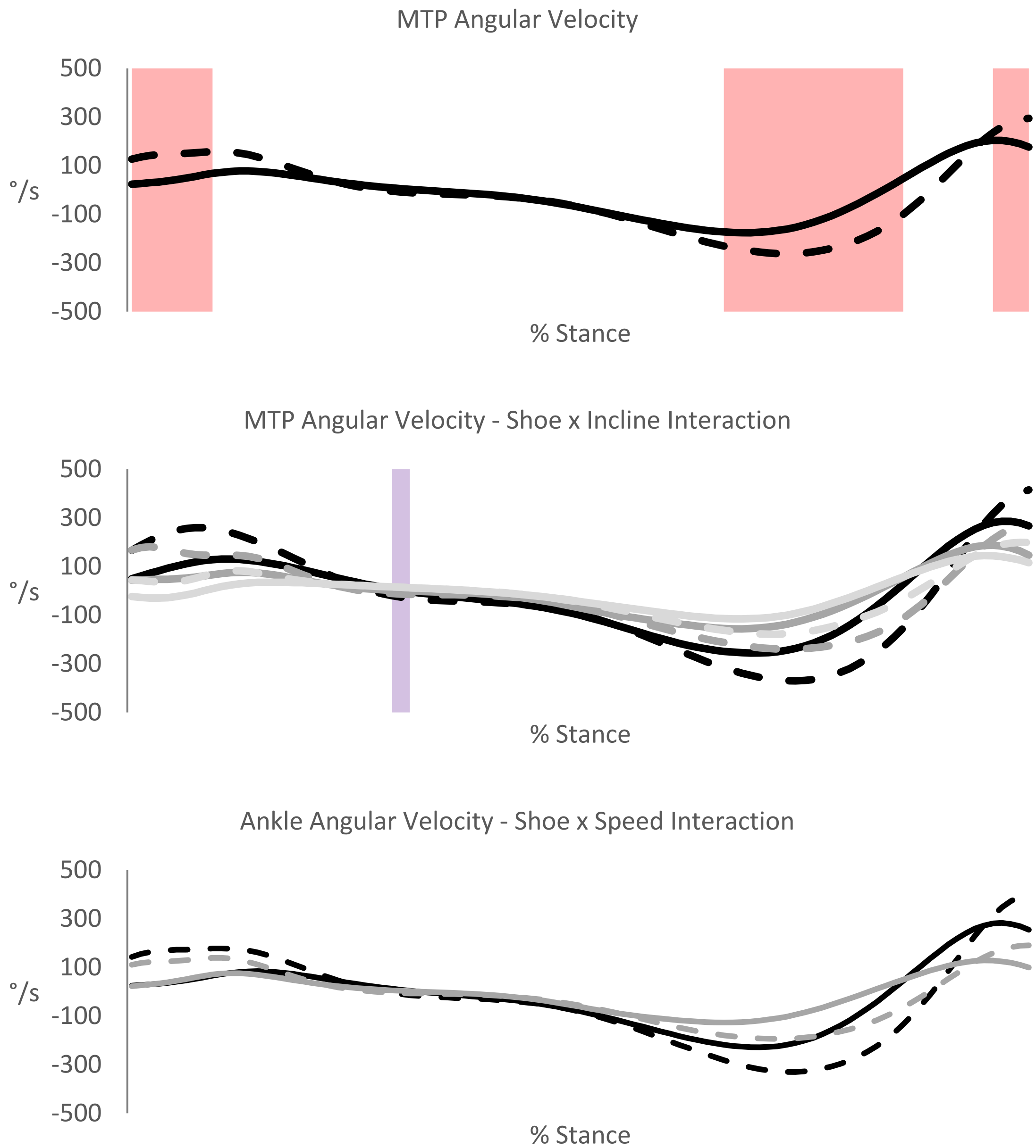

Figure 4.5.4B: MTP angular velocity was slower with the intact shoes
(Top) Average MTP angular velocity between the cut (dashed line) and intact (solid line) shoe conditions during stance. There was a significant main effect of shoe on MTP angular velocity during 0-9% ($p<0.001$), 66-86% ($p<0.001$), and 96-100% ($p=0.030$) of stance.
(Middle) Average MTP angular velocity at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was a significant shoe x incline interaction on MTP angular velocity during 30-31% ($p=0.044$) of stance.
(Bottom) Average MTP angular velocity at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on MTP angular velocity during stance.

4.5.3 MTP MOMENT

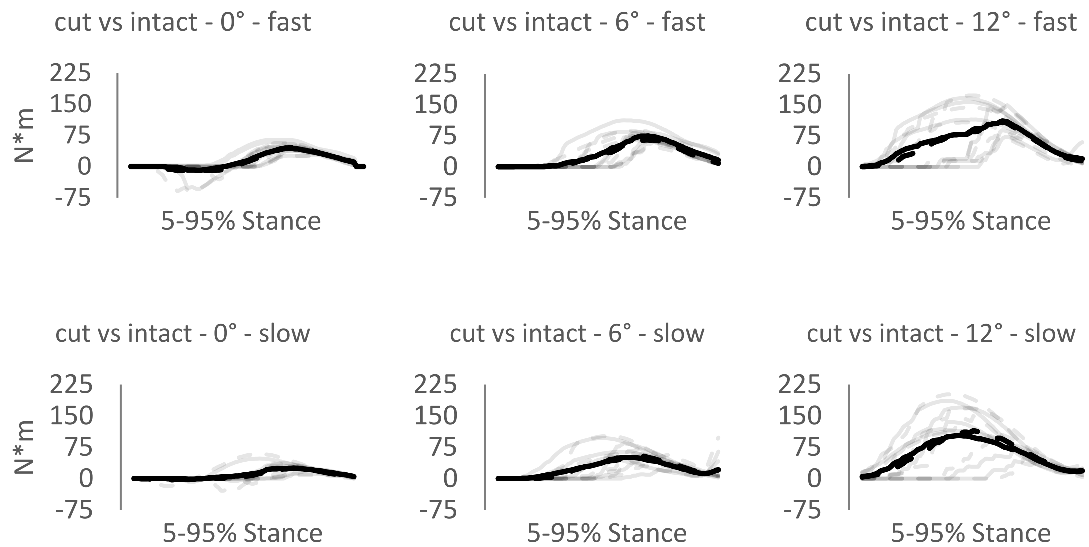

Figure 4.5.5: MTP moment during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: MTP moment (N*m) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: MTP moment (N*m) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.5.5. Overall, there was no significant main effect of shoe on MTP moment (Figure 4.5.6). However, there was a significant main effect of incline on MTP moment. Specifically, MTP moment increased as incline increased during 47-83% of stance ($p < 0.001$). There was also no significant main effect of speed on MTP moment. Moreover, there was no significant shoe × incline interaction, shoe × speed interaction, or incline × speed interaction on MTP moment.

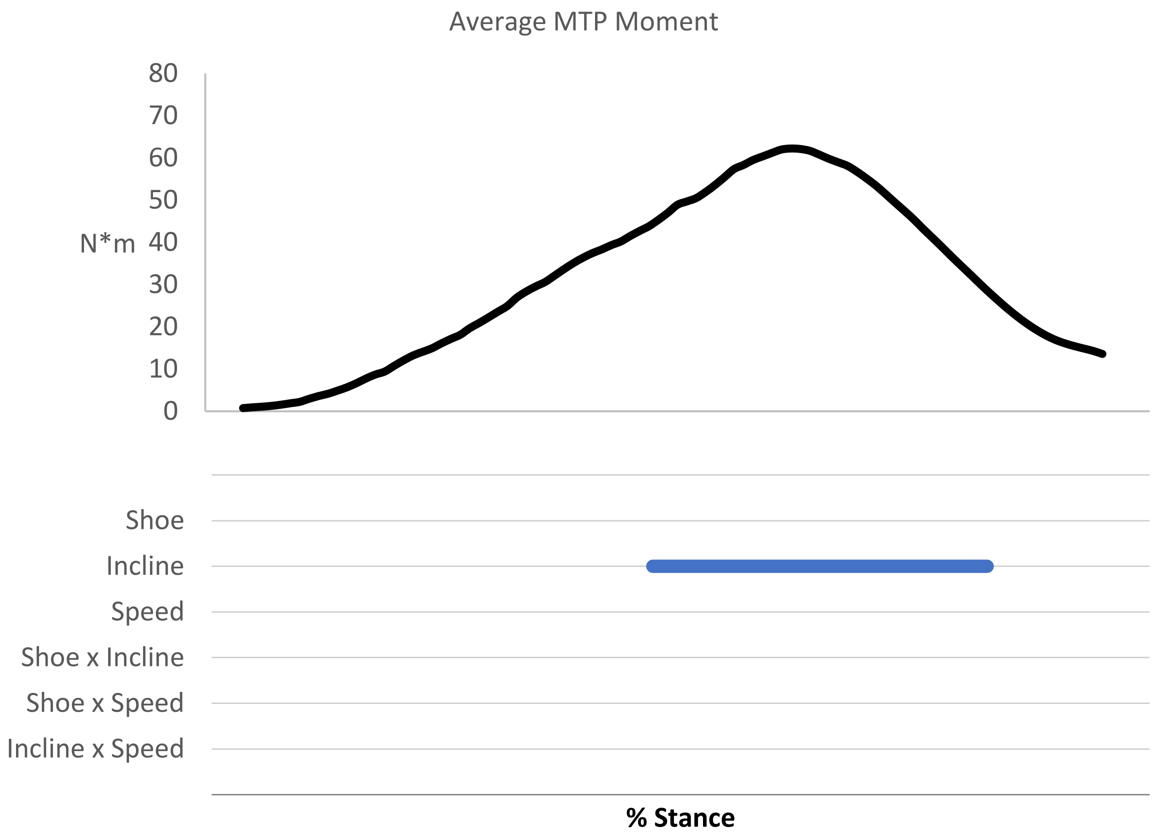

Figure 4.5.6A: MTP moments were similar between shoe conditions
(Top) Average MTP moment across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

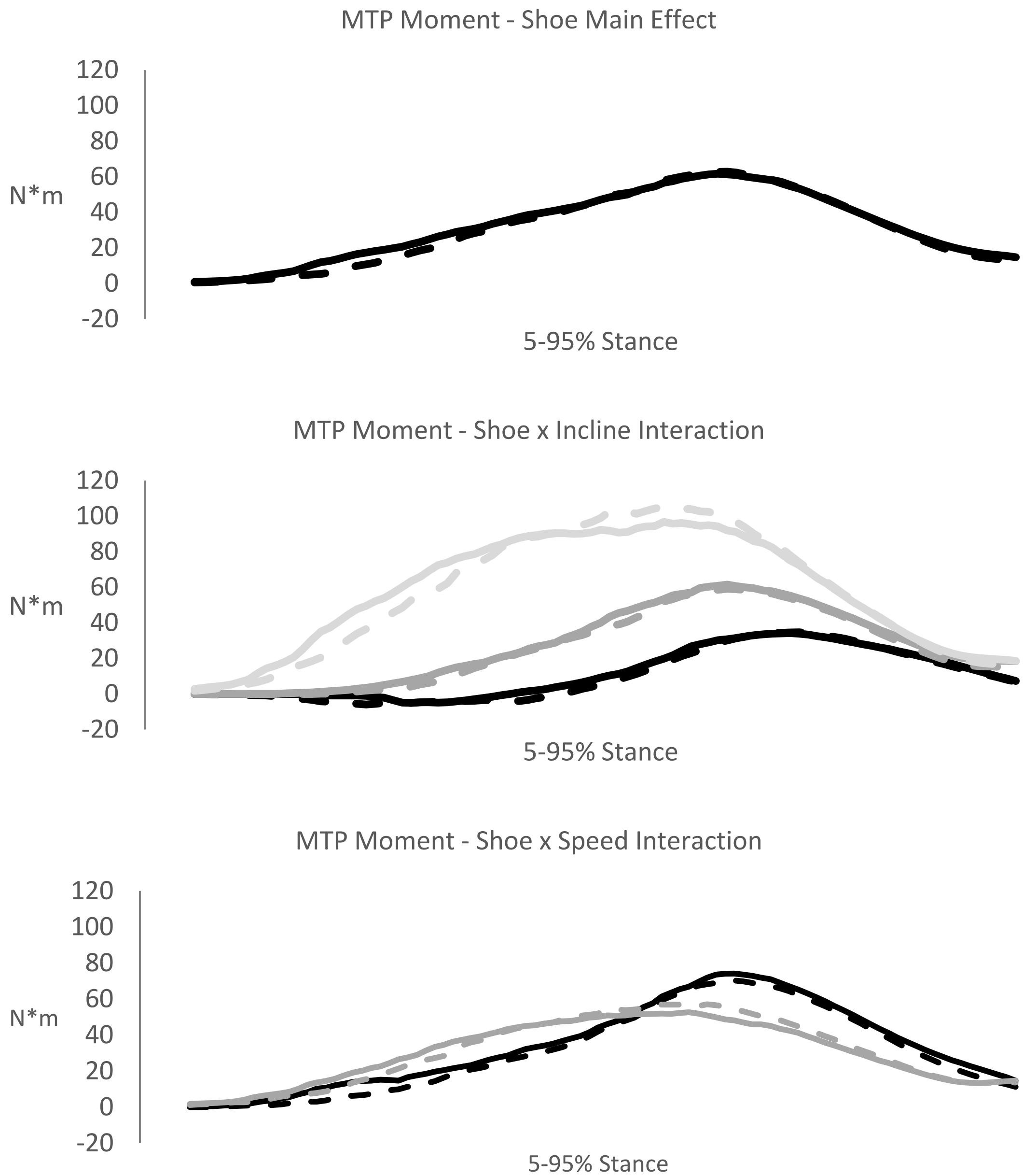

Figure 4.5.6B: MTP moments were similar between shoe conditions
(Top) Average MTP moment between the cut (dashed line) and intact (solid line) shoes during stance. There was no significant main effect of shoe on MTP moment during stance.
(Middle) Average MTP moment at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was no significant shoe x incline interaction on MTP moment during stance.
(Bottom) Average MTP moment at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on MTP moment during stance.

4.5.4 MTP POWER

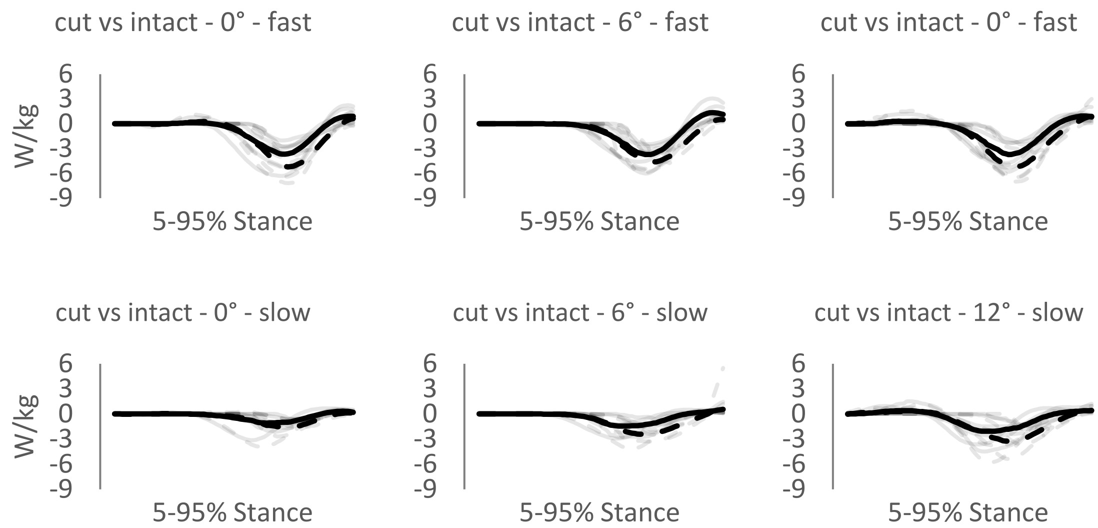

Figure 4.5.7: MTP power during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Top, left to right: MTP power (W/kg) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: MTP power (W/kg) of running conditions during 5-95% stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) running speed.

Group average data for each experimental condition is shown in Figure 4.5.7. Overall, there was a significant main effect of shoe on MTP power (Figure 4.5.8). Compared to the cut shoe, MTP power was significantly lower with the intact shoe during 64-83% of stance ($p < 0.001$). There was also a significant main effect of incline on MTP power. As incline increased, MTP power significantly increased during 51-62% ($p < 0.001$) and 82-83% ($p = 0.0498$) of stance. There was a significant main effect of speed on MTP power as well. Compared to the slow-running condition, MTP power was significantly greater at the fast-running condition during 63-64% ($p = 0.0496$) and 80-84% ($p = 0.016$) of stance. Moreover, there was no significant shoe × incline interaction, shoe × speed interaction, or incline × speed interaction.

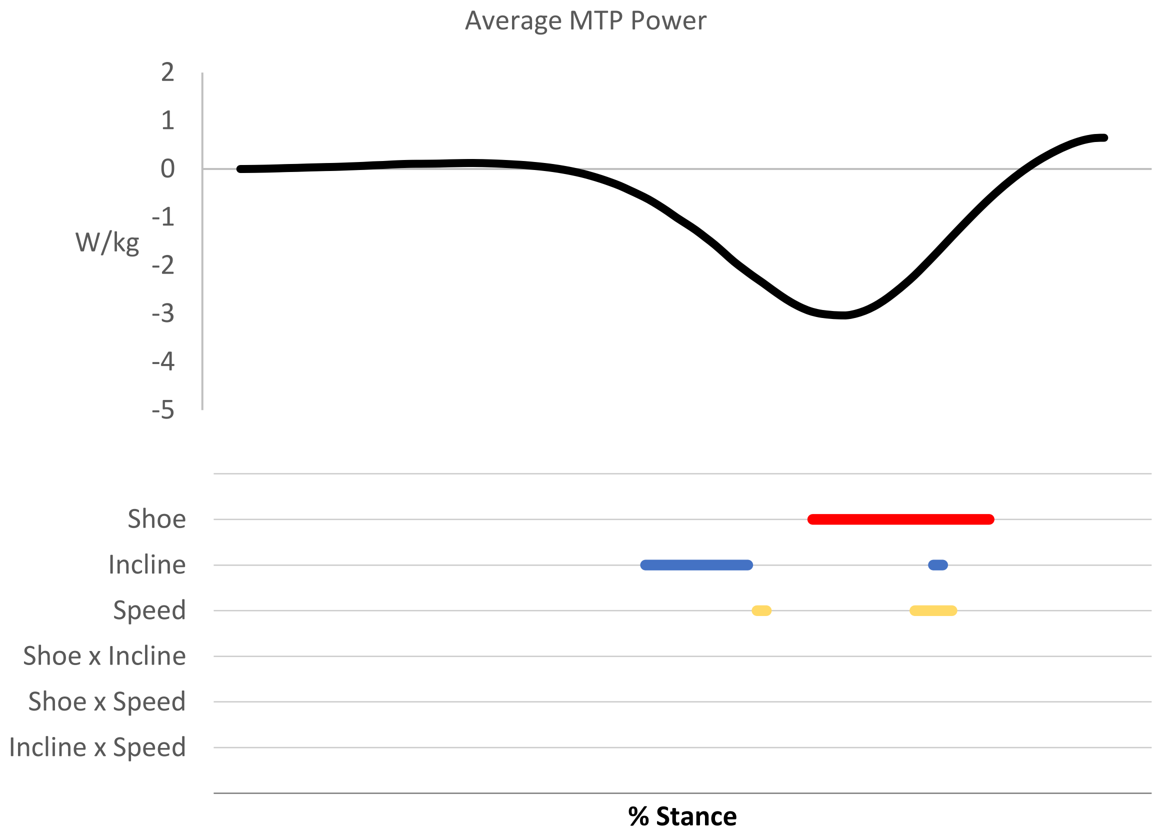

Figure 4.5.8A: MTP power was lower with the intact shoes
(Top) Average MTP power across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

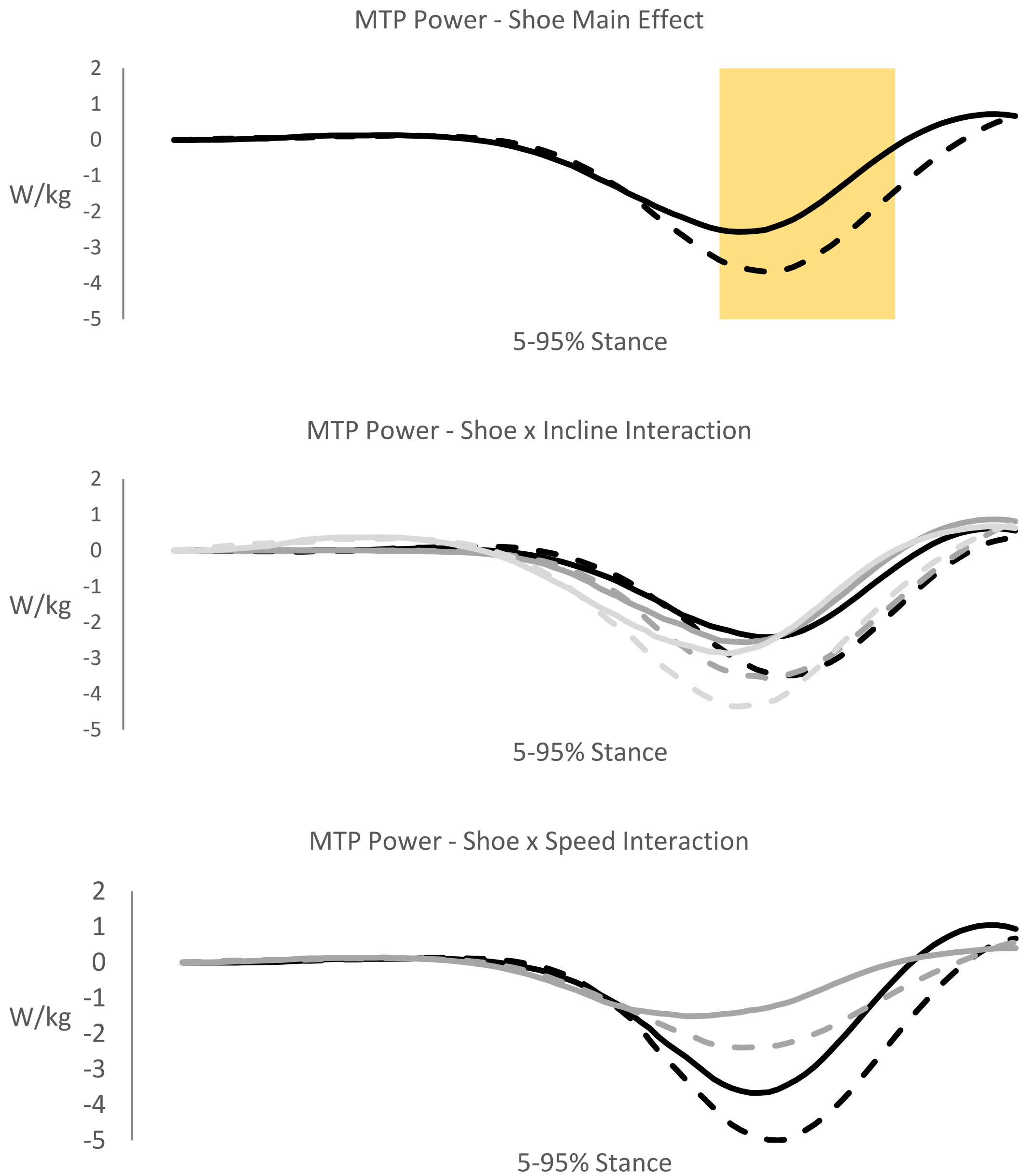

Figure 4.5.8B: MTP power was lower with the intact shoes
(Top) Average MTP power between the cut and intact shoe conditions during stance. There was a significant main effect of shoe on MTP power during 64-83% ($p<0.001$) of stance.
(Middle) Average MTP power at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was no significant shoe x incline interaction on MTP power during stance.
(Bottom) Average MTP power at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on MTP power during stance.

4.6 JOINT WORK

Negative work in the MTP joint was reduced in the intact shoes, while positive work was higher, resulting in overall less negative net work in the intact shoes. At the ankle joint, negative work was similar, but the positive work was lower in the intact shoes, resulting in overall less positive net work in the intact shoes. All of these between-shoe differences were independent of incline.

4.6.1 NEGATIVE JOINT WORK

Overall, there was a significant main effect of shoe on negative MTP work ($p < 0.0001$; Table 4.6.1). The negative MTP work was significantly less negative in the intact shoe compared to the cut shoe (Figure 4.6.1). There was also a significant main effect of incline on positive MTP work ($p < 0.0001$). The negative MTP work was significantly more negative at the 12° incline compared to the 0° ($p < 0.0001$) and 6° ($p = 0.0045$) inclines, respectively. The negative MTP work was similar between the 0° and 6° inclines. There was a significant main effect of speed on negative MTP work as well ($p < 0.0001$). The negative MTP work was significantly more negative at the fast speed compared to the slow speed. Moreover, there was no significant shoe × incline interaction or significant shoe × speed interaction. There was a significant incline × speed interaction ($p = 0.0029$), indicating that the less negative MTP work at the slow-running condition is less pronounced at the steeper inclines.

Overall, there was no significant main effect of shoe on negative ankle work (Table 4.6.1). However, there was a significant main effect of incline on negative ankle work ($p = 0.0068$). The negative ankle work was significantly more negative at the 0° incline compared to the 6° ($p = 0.0082$) and 12° ($p = 0.0378$) inclines, respectively. The negative ankle work was similar between the 6° and 12° inclines. There was also significant main effect of speed on negative ankle work ($p < 0.0001$). The negative ankle work was significantly more negative at the fast speed compared to the slow speed. There was no significant shoe × incline interaction or significant shoe × speed interaction. There was a significant incline × speed interaction ($p < 0.0001$), indicating that the less negative MTP work at the slow-running condition is less pronounced at the steeper inclines.

4.6.2 Positive Joint Work

Overall, there was a significant main effect of shoe on positive MTP work ($p = 0.0204$; Table 4.6.1). The positive MTP work was significantly greater in the intact shoe compared to the cut shoe (Figure 4.6.1). There was also a significant main effect of incline on positive MTP work ($p = 0.0005$). The positive MTP work was significantly greater at the 12° incline compared to the 0° ($p = 0.001$) and 6° ($p = 0.0042$) inclines, respectively. The positive MTP work was similar between the 0° and 6° inclines. There was no significant main effect of speed on positive MTP work. Moreover, there was no significant shoe × incline interaction, shoe × speed interaction, or incline × speed interaction.

Overall, there was significant main effect of shoe on positive ankle work ($p = 0.0204$; Table 4.6.1). The positive ankle work was significantly lower in the intact shoe compared to the cut shoe (Figure 4.6.1). There was also a significant main effect of incline on positive ankle work ($p = 0.0001$). The positive ankle work was significantly greater at the 12° incline compared to the 0° ($p < 0.0001$). The positive ankle work was similar between the 0° and 6° inclines, and between the 6° and 12° inclines. There was a significant main effect of speed on positive ankle work as well ($p < 0.0001$). The positive ankle work was significantly greater at the fast speed compared to the slow speed. There was no significant shoe × incline interaction or significant shoe × speed interaction. There was a significant incline × speed interaction ($p = 0.0004$), indicating that the less positive MTP work at the slow-running condition is less pronounced at the steeper inclines.

4.6.3 Net Joint Work

Overall, there was a significant main effect of shoe on net MTP work ($p < 0.0001$; Table 4.6.1). The net MTP work was significantly less negative in the intact shoe compared to the cut shoe (Figure 4.6.1). There was also a significant main effect of incline on net MTP work ($p = 0.0015$). The net MTP work was significantly ($p = 0.0009$) more negative at the 12° incline compared to the 0° incline. The net MTP work was similar between the 0° and 6° inclines, and between the 6° and 12° inclines. There was a significant main effect of speed on net MTP work as well ($p < 0.0001$). The net MTP work was significantly more negative at the fast speed compared to the slow speed. There was no significant shoe × incline interaction. However, there was a significant shoe × speed interaction ($p = 0.0381$), indicating the reduction in net MTP work in the intact shoes was more pronounced at the fast-running condition. There was also a significant incline × speed interaction ($p = 0.007$), indicating the less net MTP work at the slow-running condition was less pronounced at the steeper inclines.

Overall, there was significant main effect of shoe on net ankle work ($p = 0.0003$; Table 4.6.1). The net ankle work was significantly lower in the intact shoe compared to the cut shoe (Figure 4.6.1). There was also a significant main effect of incline on net ankle work ($p < 0.0001$). The net ankle work was significantly greater at the 12° incline compared to the 0° ($p < 0.0001$) and 6° ($p = 0.0046$) inclines, respectively. The net ankle work was also significantly greater at the 6° incline compared to the 0° ($p < 0.0001$). There was a significant main effect of speed on net ankle work as well ($p < 0.0001$). The net ankle work was significantly greater at the fast speed compared to the slow speed. There was no significant shoe × incline interaction, shoe × speed interaction, or incline × speed interaction.

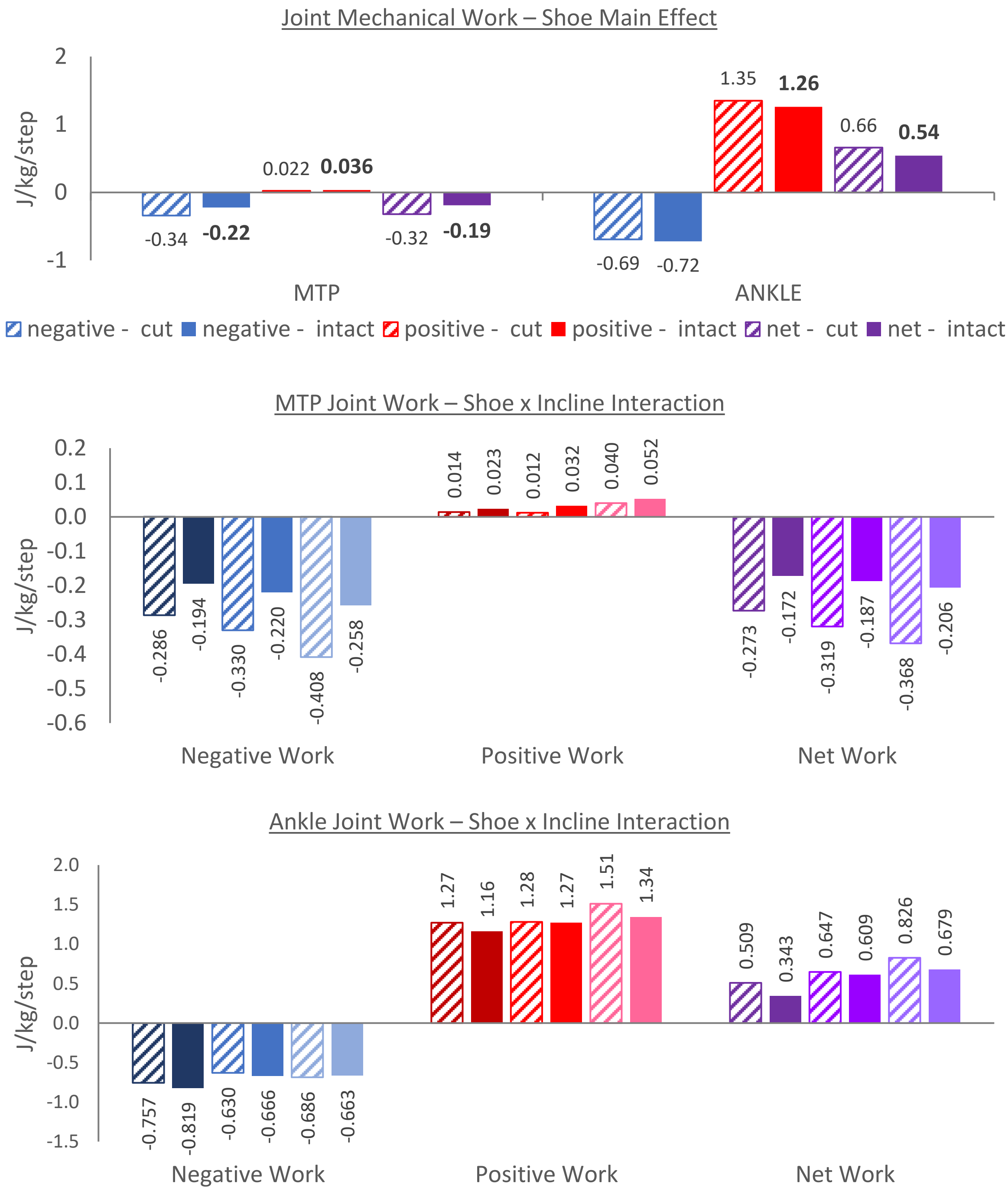

Figure 4.6.1: The high LBS intact shoes had a shoe main effect on both the ankle and MTP joint mechanical work, but these differences were independent of incline.
(Top) Average ankle and MTP joint negative, positive, and net work between the cut (dashed) and intact (solid) shoes. Bold indicates a significant difference compared to the cut shoes.
(Middle) MTP joint negative, positive, and net work between the cut (dashed) and intact (solid) shoes at the level (dark), 6° (medium), and 12° (light) inclines.
(Bottom) Ankle joint negative, positive, and net work between the cut (dashed) and intact (solid) shoes at the level (dark), 6° (medium), and 12° (light) inclines.

		0°		6°		12°	
		Cut	***Intact***	***Cut***	***Intact***	***Cut***	***Intact***
MTP Negative Work (J/kg/step)	*Fast*	-0.42 ± 0.15	-0.28 ± 0.16*	-0.41 ± 0.10	-0.30 ± 0.13*	-0.46 ± 0.13#+	-0.30 ± 0.13*#+
	Slow	_-0.15 ± 0.12_	_-0.11 ± 0.08*_	_-0.25 ± 0.08_	_-0.14 ± 0.09*_	_-0.35 ± 0.14#+_	_-0.22 ± 0.10*#+_
Ankle Negative Work (J/kg/step)	*Fast*	-1.02 ± 0.33	-1.12 ± 0.44	-0.77 ± 0.19#	-0.86 ± 0.18#	-0.74 ± 0.20#	-0.73 ± 0.23#
	Slow	_-0.50 ± 0.17_	_-0.51 ± 0.17_	_-0.49 ± 0.14#_	_-0.47 ± 0.12#_	_-0.63 ± 0.17#_	_-0.60 ± 0.14#_
MTP Positive Work (J/kg/step)	*Fast*	0.020 ± 0.025	0.031 ± 0.040*	0.009 ± 0.007	0.046 ± 0.042*	0.038 ± 0.039#+	0.053 ± 0.035*#+
	Slow	0.008 ± 0.005	0.015 ± 0.014*	0.014 ± 0.026	0.018 ± 0.008*	0.042 ± 0.036#+	0.051 ± 0.048*#+
Ankle Positive Work (J/kg/step)	*Fast*	1.61 ± 0.34	1.47 ± 0.38*	1.52 ± 0.28	1.62 ± 0.44*	1.63 ± 0.31#	1.50 ± 0.32*#
	Slow	_0.92 ± 0.28_	_0.85 ± 0.29*_	_1.03 ± 0.24_	_0.93 ± 0.21*_	_1.39 ± 0.35#_	_1.19 ± 0.24*#_
MTP Net Work (J/kg/step)	*Fast*	-0.40 ± 0.13	-0.25 ± 0.14*	-0.40 ± 0.09	-0.25 ± 0.10*	-0.43 ± 0.11#+	-0.24 ± 0.11*#
	Slow	_-0.15 ± 0.12_	_-0.09 ± 0.07*_	_-0.24 ± 0.09_	_-0.12 ± 0.09*_	_-0.31 ± 0.11#+_	_-0.17 ± 0.07*#_
Ankle Net Work (J/kg/step)	*Fast*	0.59 ± 0.19	0.35 ± 0.24*	0.75 ± 0.22#	0.76 ± 0.35*#	0.90 ± 0.15#+	0.77 ± 0.17*#+
	Slow	_0.42 ± 0.18_	_0.34 ± 0.21*_	_0.54 ± 0.16#_	_0.46 ± 0.18*#_	_0.76 ± 0.22#+_	_0.59 ± 0.17*#+_

Table 4.6.1: Comparison of negative, positive, and net joint work at the MTP and ankle joints between the cut and intact shoe conditions at each incline and their respective fast and slow running speeds.

There was a significant main effect of shoe where * indicates a significant difference between the cut and intact shoes.

There was a significant main effect of incline for where # indicates a significant difference compared to 0°, and #+ indicates a significant difference compared to 6°.

There was a significant main effect of speed where *italics* indicates a significant difference compared to the fast-running speed.

4.7 FOOT EXTERNAL ROTATION

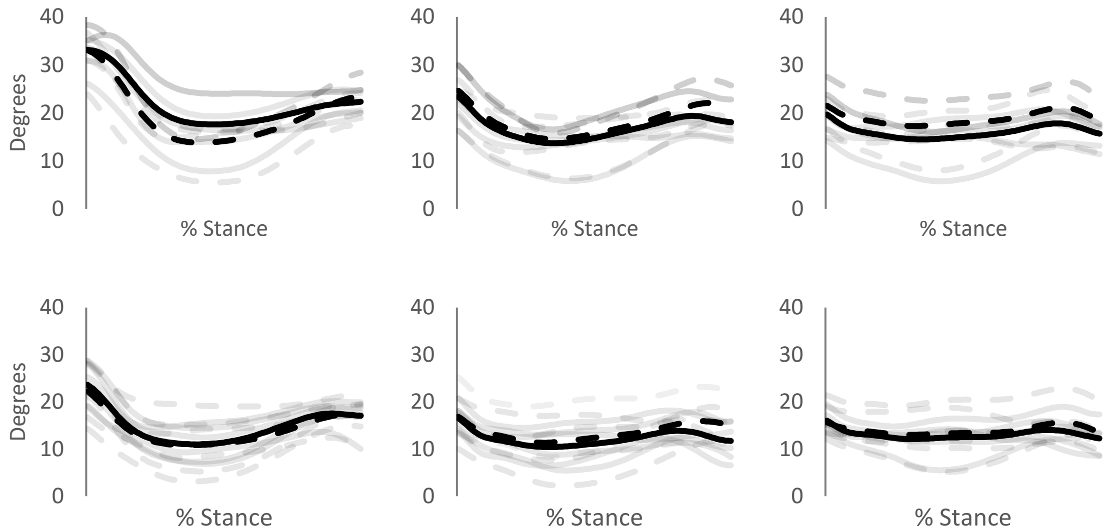

Figure 4.7.1: Foot external rotation during stance between the cut and intact shoes
Dashed lines represent the cut shoe and solid lines represent the intact shoe. Black lines represent averages and grey lines represent individual data.
Top, left to right: Foot external rotation (degrees) of running conditions during stance at the 0°, 6°, and 12° inclines at their respective fast (4.44, 2.38, 1.55 m/s) running speed.
Bottom, left to right: Foot external rotation (degrees) of running conditions during stance at the 0°, 6°, and 12° inclines at their respective slow (2.38, 1.55, 1.15 m/s) speed.

Group average data for each experimental conditions is shown in Figure 4.7.1. Overall, there was no significant main effect of shoe on foot external rotation (Figure 4.7.2). However, there was a significant main effect of incline on foot external rotation. Specifically, the foot was less externally rotated during 0-25% ($p = 0.025$) and 86-100% ($p = 0.042$) as incline increased. There was also no significant main effect of speed on foot external rotation. There was a significant shoe × incline interaction during 6-24% ($p = 0.036$) and 55-69% ($p = 0.042$) of stance, indicating that the foot became less externally rotated in the intact shoe as incline increased. There was also no significant shoe × speed interaction or incline × speed interaction on foot external rotation.

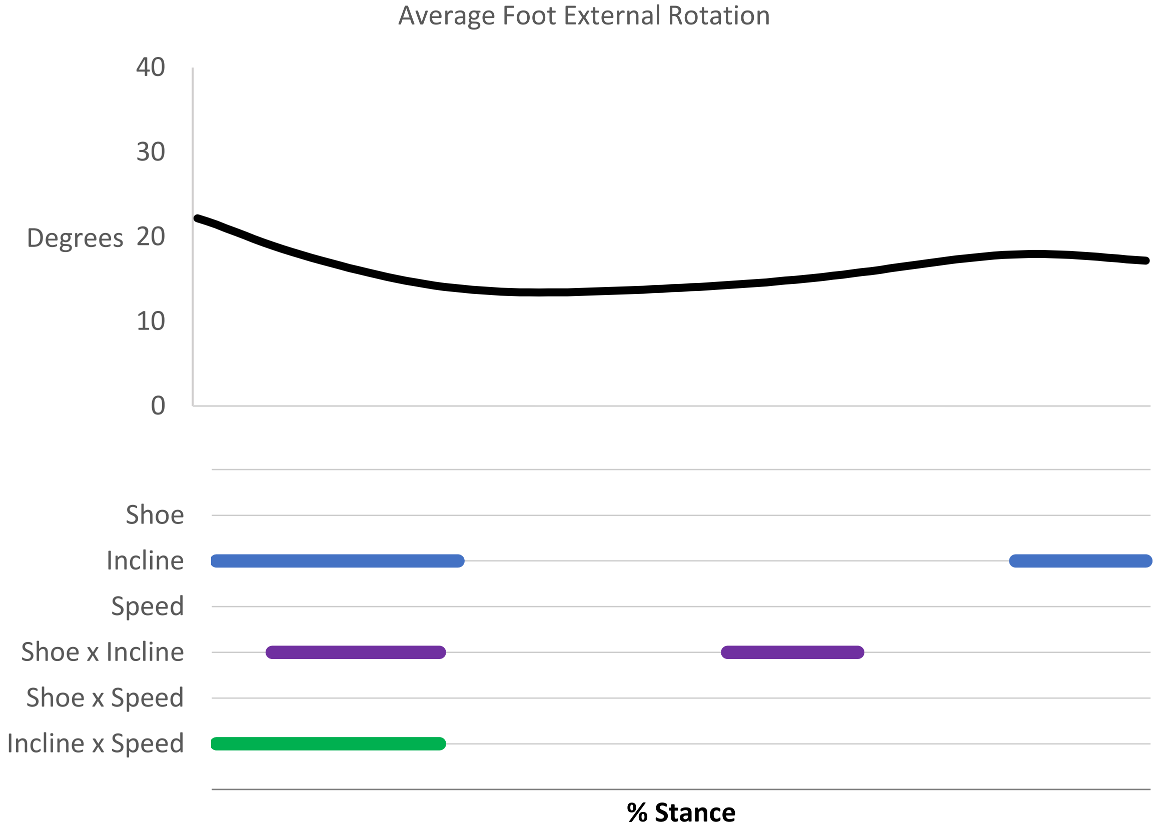

Figure 4.7.2A: Foot external rotation was greater in the intact shoes during level running but lower during graded running
(Top) Average foot external rotation across all inclines (0°, 6°, and 12°), running speeds (fast and slow), and footwear conditions (cut and intact).
(Bottom): Statistically significant SPM ranges for the main effects and interactions of incline, running speed, and footwear condition during stance.

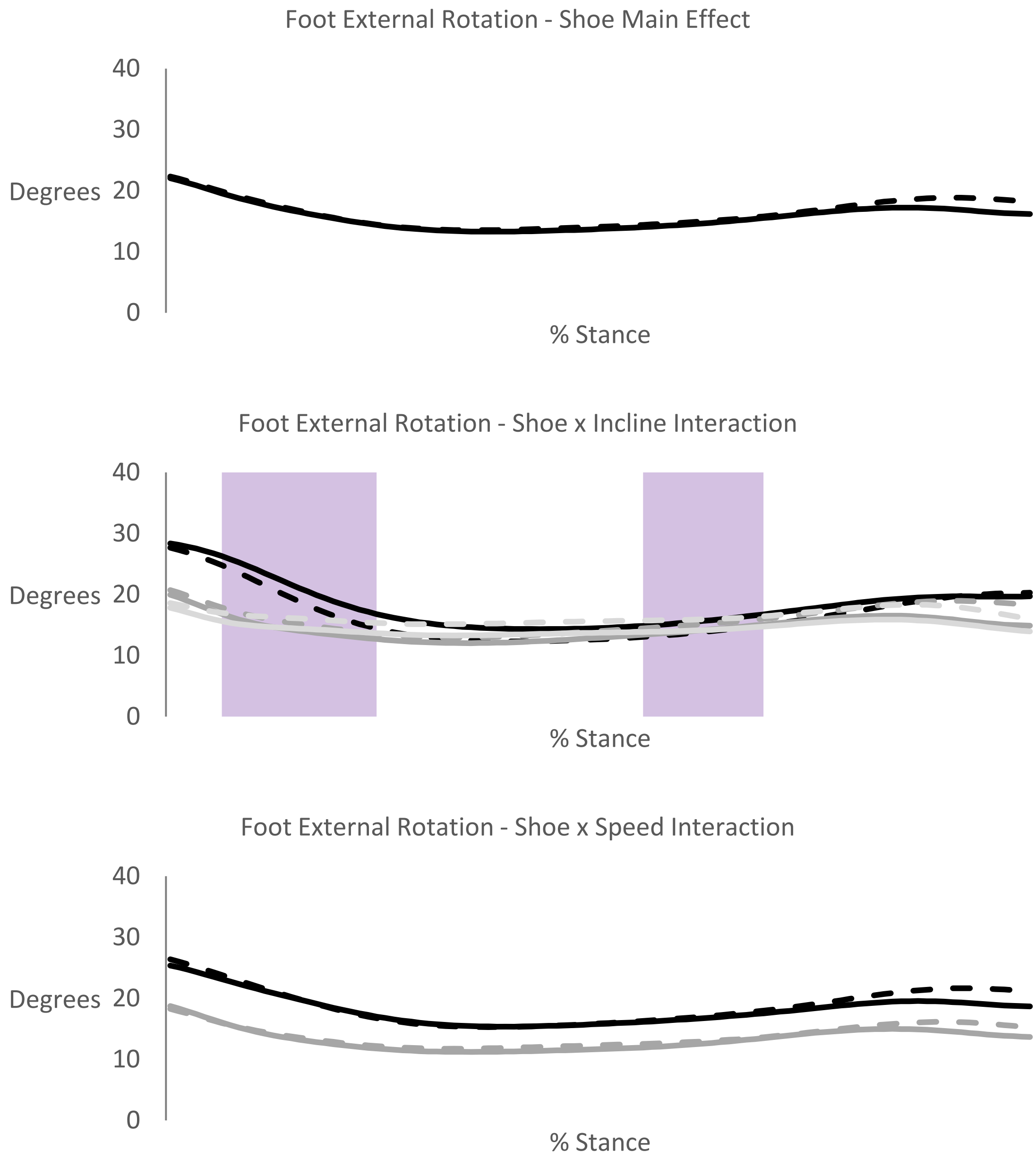

Figure 4.7.2B: Foot external rotation was greater in the intact shoes during level running but lower during graded running
(Top) Average foot external rotation between the cut (dashed line) and intact (solid line) shoe conditions during stance. There was no significant main effect of shoe on foot external rotation during stance.
(Middle) Average foot external rotation at the level (black), 6° (medium grey), and 12° (light grey) inclines between the cut and intact shoe conditions during stance. There was a significant shoe x incline interaction on foot external rotation during 6-24% ($p=0.036$) and 55-69% ($p=0.042$) of stance.
(Bottom) Average foot external rotation at the fast (black) and slow (grey) speeds between the cut and intact shoe conditions during stance. There was no significant shoe x speed interaction on foot external rotation during stance.

CHAPTER 5

DISCUSSION

Results from this study suggest that the longitudinal bending stiffness of carbon-fiber plates within the footwear midsoles has limited influence on running energetics but has considerable effects on the biomechanics of the ankle and MTP joints. This study investigated the between shoe differences across inclines in metabolic power and MTP and ankle joint angles, angular velocities, moments, powers, and work. Therefore, we focused on exploring 1) main effects of shoe and 2) shoe × incline interactions. For metabolic power, there was no significant main effect of shoe or shoe × incline interaction. At the ankle, there was a significant main effect of shoe on joint angular velocity and work; and a significant shoe × incline interaction on joint angle. At the MTP joint, there was a significant main effect of shoe on joint angle, angular velocity, power, and work; and a significant shoe × incline interaction on joint angle and angular velocity. Nevertheless, it should be noted that this study was only able to collect and use data for analysis from a limited number of participants, and therefore is underpowered, so there may be significant differences that went undetected.

5.1 METABOLIC POWER

The first aim of this study was to characterize and quantify the effects of increased footwear midsole longitudinal bending stiffness on running energetics at level, 6°, and 12° inclines. We hypothesized that the energetic benefits of the increased longitudinal bending stiffness would diminish as the running incline increased, such that the high LBS (VF_{intact}) footwear would result in energetic benefits at the level and 6° inclines, and an energetic penalty at the 12° incline, compared to the low LBS (VF_{cut}) footwear. However, this was not the case for this study, and we reject this hypothesis. The high LBS footwear condition did not result in any significant statistical improvements in running economy at any of the inclines. There was also no significant main effect of shoe or shoe × incline interaction. Interestingly, on average, there were non-significant small improvements in metabolic power (at the fast speed) with the high LBS shoes (Figure 4.1), albeit only 0.6%, 0.4%, and 0.7% at the 0°, 6°, and 12° inclines, respectively.

For level running, the current literature has found mixed results regarding the energetic effects of increased footwear midsole longitudinal bending stiffness (see Literature Review section). Nevertheless, this study found no significant effect of increased footwear midsole LBS on metabolic power for level running. The results of this study during level running are in agreement with Healey & Hoogkamer, who also found no significant statistical differences, using identical footwear conditions to the present study (Healey and Hoogkamer, 2021). In a sample of 14 runners, they found a non-significant 0.5% higher metabolic power in the cut shoes, as compared to our non-significant 0.6% higher metabolic power in the cut shoes for our 7 runners. So, while intact VF shoes have repeatedly been shown to lower metabolic power by 3-4% as compared to control shoes (Barnes and Kilding, 2019; Hoogkamer et al., 2017; Hunter et al., 2019; Whiting et al., 2021), our, and Healey & Hoogkamer's, approach of cutting the carbon fiber plates in the VF shoes (while keeping all other footwear conditions constant) resulted in small, non-significant metabolic savings, even for level running. Moreover, the variability in metabolic power responses observed in this study could have been influenced by the participants' individual response to the footwear, as others have suggested that optimal LBS differs between individuals (McLeod et al., 2020; Oh and Park, 2017) to an extent that some might be classified as non-responders (Madden et al., 2016; Willwacher et al., 2014). With our small sample size and the potential interactions with speed and incline, we did not explore this for our dataset.

To our knowledge, there are no studies that have specifically investigated the isolated effects of footwear midsole longitudinal bending stiffness on graded running energetics. This present study attempted to fill this knowledge gap within the current literature. Like our findings at level running, we found no significant statistical effect of increased footwear midsole LBS on metabolic power at both the 6° and 12° inclines. Nevertheless, to expand on the findings of Hoogkamer et al. (Hoogkamer et al., 2018), Whiting et al. investigated the metabolic effects of the carbon-plated Nike Vaporfly against control shoes during graded running and found them to have a 2.8% improvement in metabolic power compared to the more conventional pair of Nike Streak 6 shoes while running at 3.61 m/s up a 3° incline (Whiting et al., 2021). This substantial difference in metabolic power found by Whiting et al. contrasts considerably to the minimal non-significant improvements found in this present study, but was likely influenced by the confounding effects of differences with midsole foam properties and overall construction. Furthermore, Hunter et al. recently performed a similar study comparing the effects of the carbon-plated Saucony Endorphin Pro and the more conventional Saucony Type A on metabolic power while running at 3.2 m/s on a 4% grade (~2.3° incline) (Hunter et al., 2022). They found a significant 1.5% improvement during running in carbon-plated shoes, both during level and uphill running. The between shoe difference in metabolic power was again likely influenced by the confounding effects of differences in the midsole characteristics, mass, and overall construction. On average, our study found a non-significant 0.4% and 0.7% improvement in metabolic power during running in a high LBS footwear condition at the 6° and 12° inclines, respectively. Whiting et al. found a significant decrease in percent change between level running (3.8%) and uphill 3° running (2.8%), suggesting a high LBS shoe can also improve graded running metabolic power, but to a lesser extent than level running metabolic power (Whiting et al., 2021). In contrast, Hunter et al. did not find any significant energetic benefits across the grade conditions they tested (Hunter et al., 2022). This may be because their uphill running condition was only ~2.3° (4%), which might be too similar to level running. Moreover, contrary to our expectations, the present study still found an improvement in metabolic power at the 12° incline on average (although not statistically significant) for the high LBS shoes, suggesting that our speculated increased importance of metabolically more expensive positive ankle work might not occur (more on this later). Taking the findings of these studies with the present study, there are no clear indications that LBS itself substantially affects metabolic power differently during steep uphill running than during level running.

5.2 BENDING STIFFNESS OR CUSHIONING?

Compared to the high LBS (VF_{intact}) footwear condition, the differences in construction of the low LBS (VF_{cut}) footwear condition could have also affected other features of the midsole, such as cushioning, rather than bending stiffness solely. Having identical pairs of shoes with and without a carbon-fiber plate for comparison would have been ideal, but such shoes were unavailable. Therefore, our next best option was to have identical pairs of VF shoes, such that one pair was kept unaltered with each shoe's carbon-fiber plate left intact for the high LBS (VF_{intact}) footwear condition, and the other pair was modified with cuts made to and through the midsole and carbon-fiber plate for the low LBS (VF_{cut}) footwear condition.

Cutting the embedded carbon-fiber plate through the midsole successfully decreased the footwear longitudinal bending stiffness. Nevertheless, other than LBS, it is possible that making the cuts through the midsole could have also affected the overall effectiveness of the midsole's cushioning properties in the forefoot, potentially confounding the metabolic power data (Franz et al., 2012; Frederick et al., 1983; Tung et al., 2014). This could be verified through mechanical testing of the footwear conditions. We originally determined that the cut and intact shoes both had an energy return (vertical compression) of 86% for loading at the rearfoot (Table 3.1.1). Ideally, we would have also performed mechanical testing at the forefoot since that is where cuts were made through the midsole. However, accessing the forefoot area for mechanical testing requires cutting through the uppers of the shoes. Therefore, this was not feasible because the footwear conditions used in this present study are required for other ongoing studies. Although we were unable to directly quantify any potential differences in the effectiveness of the foam between the footwear conditions, our experimental outcomes can be used to infer possible discrepancies.

For example, cushioning can be expected to be more effective at faster running speeds with greater ground reaction forces. With the slower running speeds during the inclined running conditions (to maintain a constant metabolic power) of the experimental protocol of this present study, subjects altered their running patterns. At the relatively fast running conditions during level running there is a clear flight phase, but subjects could transition their gait to grounded running at the relatively slow running conditions during inclined running (especially for the slow conditions). There were four subjects in this present study with a >50% duty factor at the slow (1.15 m/s) 12° incline running condition. With this change in running pattern, the effects of the footwear conditions could be different for grounded running than (slow) aerial running. Grounded running has been found to decrease vertical ground reaction force and vertical instantaneous loading rate (musculoskeletal loading) (Bonnaerens et al., 2019; McMahon et al., 1987). Characterized by lowered GRFs, grounded running could limit the metabolic savings from highly-cushioned shoes. For the slow 12° conditions of the present study, there were six running trials with grounded running (duty factor >50%). Consistent with the literature, the vertical GRFs for these grounded running trials were lower than for slow aerial running (Figure 5.2.1). Therefore, if cutting through the midsole had a considerable effect on cushioning, we would expect our experimental outcomes to capture shoe × incline interactions such that metabolic rate was substantially higher in the cut than in the intact shoes during level running (relatively fast running speeds, i.e. speeds > walk-run transition) with diminishing differences during inclined running. However, this was not the case.

Moreover, subjects tend to run with more of a forefoot strike pattern during uphill running (Vernillo et al., 2017). This was true for the present study (Figure 4.3.1). With more forefoot striking during uphill running, differences in forefoot cushioning could have affected our experimental outcomes. If the forefoot cushioning was reduced in the cut shoes, we would expect less metabolic savings in the cut shoes for uphill running with more pronounced forefoot striking. However, this was not the case, and we found that the metabolic powers of running in the cut and intact shoes were similar (Figure 4.1.1).

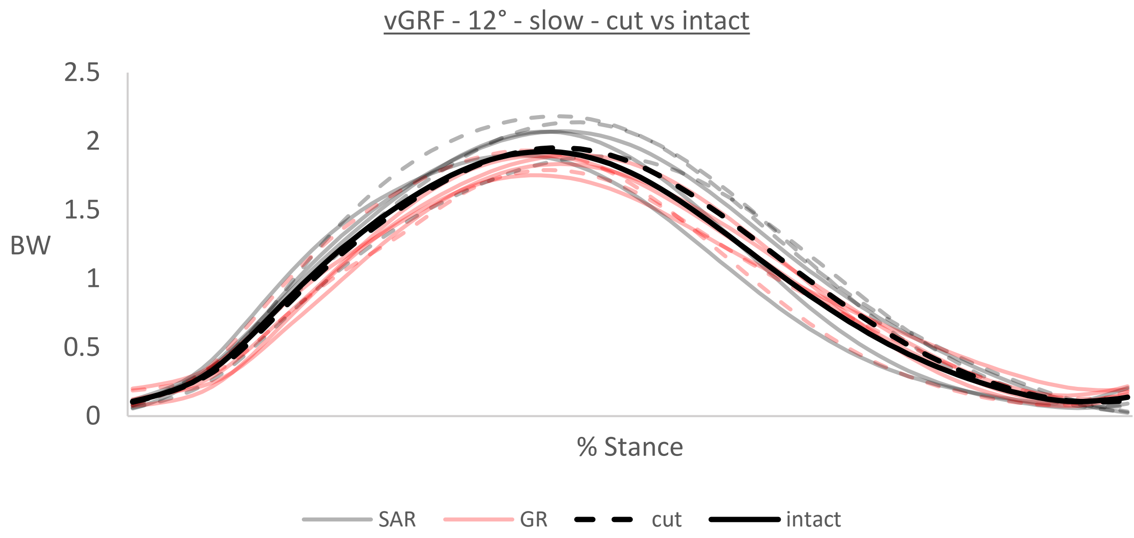

Figure 5.2.1: Vertical GRFs were generally lower during grounded running.
Dashed lines represent the cut shoe and solid lines represent the intact shoe.
Individual running trials with grounded running (GR) shown in red.
Individual running trials with slow aerial running (SAR) shown in grey.
Average vertical ground reaction forces (BW) during stance at the slow (1.15 m/s) 12° incline running condition shown in black.

5.3 SPATIOTEMPORAL PARAMETERS

Spatiotemporal parameters were similar between the VF_{cut} and VF_{intact} shoes. There were no significant differences in contact time, step frequency, and duty factor. Previous research has shown that there is an inverse relationship between contact time and metabolic rate (Hunter et al., 2019). Comparing the footwear conditions, this present study found a 2.4% difference (although, not statistically significant), with the average contact time of 0.292±0.060 seconds in the cut shoe 0.299±0.064 seconds in the intact shoe. Therefore, the similar contact times in the cut and intact shoes may contribute to the absence of a significant main effect of shoe on metabolic power in this present study. Healey & Hoogkamer found a significant 1% difference in contact time between the cut and intact shoes during level running, although they also did not find significant differences in metabolic power. Since step frequency and duty factor derive from contact time, it is reasonable that they had no significant differences.

5.4 JOINT MECHANICS

The second aim of this study was to characterize and quantify the effects of increased footwear midsole longitudinal bending stiffness on the ankle and MTP joint mechanics during running at level, 6°, and 12° inclines. We hypothesized that a high LBS footwear condition would: a) decrease MTP joint dorsiflexion, moment, and negative work, and b) decrease ankle joint dorsiflexion, moment, negative work, and positive work. Regarding the MTP joint, there was a significant main effect of shoe and our findings showed that high LBS did result in decreased dorsiflexion and negative work, but not moment. Regarding the ankle, there was a significant main effect of shoe and our findings showed that high LBS did result in decreased positive work, but not dorsiflexion, moment, or negative work. Furthermore, there was a significant shoe × incline interaction on MTP angle and angular velocity, and ankle angle.

Our results indicated that a high LBS footwear condition significantly influences MTP joint angle, but not ankle angle. There was a significant main effect of shoe on MTP angle. Compared to the VF_{cut} (low LBS) shoe, the VF_{intact} (high LBS) shoe had an overall effect of decreasing MTP dorsiflexion during foot-strike and toe-off (Figure 4.5.2). This shows that the VF_{intact} shoe condition was sufficiently stiff to limit bending of the MTP joint. This is consistent with previous studies that found decreased MTP joint dorsiflexion during level running in footwear with flat (Flores et al., 2019; Madden et al., 2016; Willwacher et al., 2013) and curved (Hoogkamer et al., 2019) carbon-fiber plates, respectively. Hoogkamer et al. had originally found that the high LBS VF shoes, compared to the Adidas Adios Boost and Nike Streak 6, significantly decreased peak MTP dorsiflexion by ~6° and ~12°, respectively. This difference in MTP angle accompanied a significant ~4% improvement in metabolic power, (Hoogkamer et al., 2019). Interestingly, the present study also found a ~6° decrease in peak MTP dorsiflexion during level running in the intact shoes compared to cut shoes, but no significant improvement in metabolic power. This suggests that, if the bending of the MTP joint is related to metabolic power, footwear characteristics such as midsole foam properties, stack height, and/or toe-spring likely have a more considerable effect than LBS. With a significant main effect of incline on MTP angle, this ~6° difference increased to a ~8° difference (Figure 4.3.2) between the intact and cut shoes during graded running, without any significant differences in metabolic power.

There was no significant main effect of shoe on ankle angle. The ankle angles were similar between the VF_{cut} and VF_{intact} shoes across inclines. During level running, the current literature has found mixed results on ankle mechanics. Originally, Hoogkamer et al. found that the VF shoes during level running resulted in less ankle dorsiflexion compared to footwear with lower LBS (Hoogkamer et al., 2019). However, they compared the VF shoes with different shoe models (Nike Streak 6 and Adidas Adios Boost), therefore it is possible that the differences they found resulted from differences other than LBS. Nevertheless, the minimal differences in level running ankle mechanics of the present study agree with Healey & Hoogkamer who used the same footwear conditions (Healey and Hoogkamer, 2021).

The increased inclines also influenced the effects of the shoes. Although there was no significant main effect of shoe on ankle angle, there was significant shoe × incline interaction on ankle angle during 85-100% of stance, indicating that the ankle angle was more plantarflexed in the cut shoes than the intact shoes at the steepest incline. In addition, there was also a significant shoe × incline interaction on MTP angle during 73-90% of stance, indicating that the reduced dorsiflexion angle in the intact shoe condition was more pronounced at the steeper inclines. An increase in flexion in the cut shoes was expected with an increase in incline. Together, these differences show that high LBS footwear can affect MTP joint and ankle angles at relatively steeper inclines like 6° and 12°.

The MTP joint and ankle moments were similar between the VF_{cut} and VF_{intact} shoes. This is in line with the findings of Healey & Hoogkamer, who also used the same footwear conditions as the present study and found no differences in MTP joint moment during level running (Healey and Hoogkamer, 2021). With these minimal non-significant differences in MTP (Figure 4.3.6) and ankle (Figure 4.2.6) moments, the significant differences in joint power and work are mainly due to differences in angular velocities (Figure 4.3.3, Figure 4.2.3). Nevertheless, it is important to note that the joint moment we calculated was produced by both the foot and the shoe. Although it cannot be quantified by our current data, it is possible that there were changes in the moments generated in the foot itself that went undetected. Moreover, the absence of significant differences with the MTP and ankle moments could have been because the high LBS shoe condition was too stiff for the subjects we recruited, possibly causing them to overcompensate by increasing foot external rotation angle during push-off, especially during steep uphill running. During push-off, we had originally expected that the high stiffness of the intact shoes would be difficult to overcome at the steep 12° incline, leading to greater foot external rotation compared to the cut shoes. High LBS footwear could limit the foot's ability to bend the shoe and contribute to an increase in foot external rotation as a potential overcompensation strategy to help modulate increases in joint moments. However, we found no significant shoe × incline interaction on foot external rotation during push-off. This suggests that subjects, while running in the intact shoes, did not module foot external rotation in response to changes in joint moments during push-off. Interestingly, although nonsignificant, foot external rotation on average was greater in the low stiffness cut shoes than the high stiffness intact shoes during push-off. During 6-24% and 55-69% of stance, the foot external rotation angle was greater in the intact shoes compared to the cut shoes for level running. However, it was the opposite during graded running. The foot external angle became lower in the intact shoes at the 6° and 12° inclines. This difference between level and graded running could be because of the difference in running speeds at the various inclines. Furthermore, minimal variability can be expected during mid-stance, and this could contribute to the significant statistical shoe × incline interaction during 55-69% of stance.

There was a significant main effect of shoe on MTP power, which lead to a significant main effect of shoe on MTP negative, positive, and net work. In contrast, there was no significant main effect of shoe on ankle power, which still lead to a significant main effect of shoe on ankle positive and net work, but not negative work. There were no significant shoe × incline interactions on joint power and work for both the MTP and ankle joints. On average, MTP power was significantly less negative in the VF_{intact} shoes. Accompanying the significant reduction in MTP joint dorsiflexion in the VF_{intact} shoes, there was a significant main effect of shoe on MTP negative work. Compared to the VF_{cut} shoes (-0.34 J/kg/step), the MTP negative work was significantly less negative in the VF_{intact} shoes (-0.22 J/kg/step). There was also a significant main effect of shoe on MTP positive work. Compared to the VF_{cut} shoes (0.022 J/kg/step), the MTP positive work was significantly greater in the VF_{intact} shoes (0.036 J/kg/step). This is in line with previous studies

(Hoogkamer et al., 2019; Willwacher et al., 2021, 2013), suggesting that this difference in positive work can partly be attributed to energy return from the bending of the carbon-fiber plate. For the ankle, there was no significant main effect of shoe on ankle negative work, but there was one on ankle positive work. The ankle negative work was similar between the VF_{cut} (-0.69 J/kg/step) and VF_{intact} shoes (-0.72 J/kg/step). The average ankle positive work in the VF_{intact} shoes (1.26 J/kg/step) was significantly lower compared to the VF_{cut} shoes (1.35 J/kg/step). This is consistent with the significant ankle plantarflexion differences from the shoe × incline interaction. Moreover, Willwacher et al. performed a similar study as ours investigating the effects of midsole bending stiffness on joint work during level and inclined running. Overall, our findings in ankle and MTP joint work were consistent with their findings (Willwacher et al., 2021). They had subjects run at 3.5 m/s at a 10% incline (~6 degrees). Their footwear conditions consisted of low stiffness shoes with no carbon-fiber plate and cuts made through the midsole, medium stiffness shoes with a flat carbon fiber plate, high stiffness shoes with a flat carbon fiber plate, and another pair of high stiffness shoes but with a curved carbon-fiber plate. Like the present study, they also found significant shoe main effects on positive MTP work, negative MTP work, net MTP work, and net ankle work. In contrast to our findings, Willwacher et al. also found a significant shoe × incline interaction on positive MTP work. They found increases in positive MTP work with slope in their high stiffness shoes, but not in their low stiffness shoes. Nevertheless, this interaction seems to be more so driven by differences between downhill and level running, rather than between level and uphill running. Further, their stiff footwear conditions utilized carbon-fiber plates that were placed under the insoles shoes, and our high stiffness shoe (VF_{intact}) condition had a carbon-fiber plate embedded in the midsole.

We initially hypothesized that there would be considerable shoe × incline interactions at the ankle that would contribute to a metabolic improvement in the high LBS VF_{intact} shoes during level and shallow 6° running, and a metabolic penalty during steep 12° running. However, there were no significant shoe × incline interactions in ankle angular velocity, moment, power, and work. In hindsight, it appears that increases in ankle angular velocity and moment with steeper inclines did not occur because, by design, the running speed decreased with steeper incline. Nevertheless, these findings all together suggest that between shoe differences are mainly independent of incline over our tested range, even though the difference in ankle angle can influence where muscles act on their force-length curves. Overall, the minimal differences in ankle mechanics are consistent with the minimal differences in metabolic power. All between shoe differences in metabolic power and MTP and ankle joint mechanics (angle, angular velocity, moment, power, and work) were independent of incline, except for ankle angle, MTP angle, and MTP angular velocity. The minimal non-significant differences in metabolic power across inclines between shoes were reasonable given the absence of shoe × incline interactions in MTP and ankle mechanical power and work. With minimal shoe × incline interactions, our findings suggest that the effects of modern high LBS racing shoes for level running are largely translatable to steep uphill running.

5.5 LIMITATIONS AND FUTURE DIRECTIONS

A potential limitation of this study is how we determined the incline-speed combinations for the experimental protocol. We were interested in investigating relatively steep inclines, but it wouldn't have been practical to have subjects run the same speed at level and up 12°. Therefore, we used an equation developed by Hoogkamer et al. to adjust running speeds such that the metabolic demand at the inclined running conditions matched the metabolic demand at level running (Hoogkamer et al., 2014). This provided a means to better allow participants to complete the running trials at a submaximal effort necessary for obtaining accurate metabolic data. Although the equation by Hoogkamer et al. accounted for various uphill running inclines from 0°–9° and speeds from 2.0–3.0 m/s, our steep 12° incline and fast (4.44 m/s) level running conditions were outside of those respective ranges. Therefore, this could have contributed to the variability of our non-significant metabolic power results.

Furthermore, the subjects of this study could be considered another limitation. The subjects we recruited also had limited experience with steep uphill treadmill running. The experimental protocol of this study did include a familiarization period (two minutes each for level, 6°, and 12°) prior to the running trials, but it may have not been enough. More habituation could have helped reduce the variability of the metabolic power outcomes. In addition, the only subjects recruited for this study were males. Prior work (Barnes and Kilding, 2019) has found that there was no significant difference with metabolic power in the VF shoes between males and females, but anatomical differences (such as body mass and leg length, etc.) can theoretically affect the effectiveness of the carbon-fiber plate and influence running mechanics and energetics. Future research can address this and recruit both males and females.

The understanding of uphill running biomechanics is currently relatively limited, but uphill running has been found to increase power output at all joints, particularly the hip (Khassetarash et al., 2020; Vernillo et al., 2020, 2017). However, the present study focused on investigating the ankle and MTP joints because the VF shoes were found to have a limited effect on the knee and hip joints during level running (Hoogkamer et al., 2019). Therefore, future studies can examine if the significant effects of high LBS footwear on ankle and MTP joint mechanics influences other joints like the knee and hip.

Future work can also investigate midsole LBS effects with more ecological shoe conditions. For uphill road running (ex: Mt. Washington), it would be interesting for future studies to compare various types of footwear like road flats vs highly cushioned carbon-plated shoes (ex: Nike Vaporfly). For uphill trail running, surfaces can range from simple dirt paths to more technical patches of mud and rock, etc. It would also be interesting for future studies to explore how footwear specifically designed for trail running (ex: Speedland SL:PDX) perform on less technical running surfaces at various inclines. This could provide insight into the similarities and differences between graded treadmill running and outdoor trail running.

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