POLITECNICO DI TORINO

Collegio di Ingegneria Chimica e dei Materiali

Master of Science Course
in Materials Engineering

Master of Science Thesis

The influence of Maximalist and Conventional midsole shoes on dynamic stability and complexity during running movement

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November 2022

Table Of Contents

Abstract

Trail running is an increasingly popular running discipline which requires mental and physical endurance. Most of times, running takes place on unpaved surfaces, with rocks, moss and grass. To minimize the risk of lower limb injuries, an optimal choice of footwear is critical before starting practise. Scientific evidence suggests that footwear (insole, outsole and midsole) may play an important role in lower body injuries. In particular, the midsole represents the connection between runners and ground and could be responsible for variability in running movement.
Over the years, the concept of variability moved from an idea of noise on top of an ideal movement pattern, to an idea of interaction between self-organization and constraints, according with the Dynamical System Theory. Variability is considered a deterministic feature instead of a stochastic process. As happens in all deterministic systems, nonlinear dynamics tools allow to monitor the evolution variability during time. The same tools, i.e. Lyapunov Exponents and Sample Entropy to quantify dynamical stability and movement complexity, respectively, may be used for describing the variability of human lower limb movement also during running.
Previous studies investigated the effects of footwear on human movement patterns during running but they finding that the dynamical stability in motion was only dependent on the experience level. No differences between Minimalist and Conventional footwear variability motion were found with Detrended Fluctuation Analysis, while predictability of the centre of mass, detected by Sample Entropy, was significantly different on the treadmill. Despite that, we are not aware of any studies that would to compa re Maximalist and Conventional footwear specifically designed for trail running.
The goal of this study was to evaluate the variability and predictability of the kinematic movement pattern of the lower limb comparing two different trail running footwear, one Conventional (Terrex Speed SG, Adidas®) and the other Maximalist (Olympus 4, Altra®), using Nonlinear Dynamics tools such as Lyapunov Exponents (LyE), and Sample Entropy (SampEn). Local dynamical stability and movement predictability or complexity are studied recording runners' movements via inertial measurement units (IMUs). The LyE and SampEn entity change represents the amount of variability and predictability in the motion pattern.
In addition, a kinematic approach of joint angles variation between Maximalist and Conventional footwear is considered as a part of stability analysis. According to the different types of footwear, lower limbs joints angles may change and possibly influence the complexity and stability running movement.
Maximalist footwear provides a lower local dynamical stability at the ankle and knee joints, with significant and almost significant results for the former and latter respectively, whereas there is not an evident predictability/complexity and stability trend at the hip joint level. The higher instability observed with Maximalist footwear might potentially increase the injury risks during trail running activity.

Keywords: *Trail running; Maximalist footwear; Conventional footwear; Lyapunov Exponents, Sample Entropy; Local dynamic stability; Lower Limbs Kinematic;*

Summary

The first part of Chapter I explained in general terms what biomechanics is, where the name comes from, how it is composed and what physical or mechanical parameters are used in biomechanics. The second half of the same chapter presented a list of possible movements that our body, especially the lower body, can perform in three-dimensional space and in three directions, focusing on rotation and the anatomical structure of hip, knee and foot joints. The second chapter discussed the division into phases of an entire running cycle movement, thoroughly identifying the most important parameters. In the third chapter, the large family of Dynamics System was described, including the non-linear dynamics tools: Lyapunov Exponent and pattern Sample entropy, two important tools for evaluating the stability and complexity of running movements. Then, in Chapter 4 Maximalist, Conventional and Minimalist shoes were compared in their properties and characteristics and the different solutions were described. Chapter 5 then presented the protocols, instruments and materials used in the data collection. Finally, the last chapters highlighted differences and comparisons in terms of stability, complexity and kinematics of the running movement between a Maximalist and a Conventional footwear.

To meet the requirements for a Master of Science in Materials Engineering, an abstract of the thesis has been prepared here in Italian. Important graphics and images have been taken from the English-language thesis and also used here.

Introduzione e Obiettivo del Progetto di Tesi

La *Biomeccanica* è una branca della scienza che insieme ad "Excercise Physiology" e molte altre, compongono la ben più conosciuta *Chinesiologia*. Combinazione di due parole: *"Bio"* e *"Meccanica",* la Biomeccanica viene di fatto definita come: *"La scienza che studia l'applicazione delle forze e gli effetti che esse producono su di un essere vivente"*. Dal momento che con il termine biomeccanico si fa riferimento a qualunque movimento generato da una forza, nel caso specifico in cui, ci si riferisca ad un ambito prettamente sportivo, viene più dettagliatamente definita come: "Sport and exercise biomechanics" [1].

Con il prefisso "Bio" si richiamano strettamente i principali sistemi organici, tra cui quello scheletrico, muscolare e nervoso; mentre con il termine "Meccanica" si considera tutta la sfera di appartenenza allo studio di modelli che si affidano alla fisica classica. A dimostrazione del fatto che serva un modello preciso a sufficienza per descrivere il moto, ma semplice abbastanza da essere quantificabile attraverso la matematica, la struttura corporea è considerata come la composizione di "Corpi Rigidi" legati tra loro attraverso articolazioni, a formare una "catena cinetica" funzionale al movimento da compiere [2].

La biomeccanica che studia quindi il corpo come un movimento di corpi rigidi concatenati tra di loro, la loro coordinazione reciproca che i segmenti rigidi hanno, la complessità e la stabilità intesa come variazione o riproducibilità di un ciclo sempre identico di corsa o camminata per esempio, durante il moto. Nella moltitudine di strumenti matematici applicabili per descrivere la coordinazione la "*Continuous relative phase*" o il *"Vector coding"*. Entrambe le tecniche descrivono esaustivamente la coordinazione di un movimento, ma non sono ottimali per stabilità e complessità, dal momento che non restituiscono mai la posizione assoluta nello spazio del segmento corporeo considerato, bensì sempre relativa ad un altro segmento, anch'esso mobile nello spazio, in una sorta di coupling. Inoltre, il modello a Vector coding necessita in input anche di punti equi-intervallati, mascherando informazioni e limitandone la successiva analisi statistica dei dati [3].

Altri metodi invece, pur sempre afferenti ai Sistemi dinamici non lineari, come gli *"Esponenti di Lyapunov"* o la *"Sample Entropy",* permettono di valutare in maniera accurata: sia la stabilità (con la prima tecnica) che la complessità (con la seconda) fornendo informazioni sull´evoluzione temporale del segnale, le quali non sarebbero reperibili per mezzo delle tradizionali grandezze statistice (deviazione standard etc).

L'obiettivo di questa tesi è un'indagine sulla stabilità e complessità degli arti inferiori durante la corsa al variare della calzatura indossata. Attraverso una valutazione con gli Esponenti di Lyapunov e la Sample Entropy, una scarpa "Maximalist" (Altra® Olympus 4) e l'altra "Coventional" (Adidas® Terrex Speed SG) sono state confrontate su quale delle due rendesse la traiettoria di corsa maggiormente stabile e meno complessa. A otto soggetti maschi è stato chiesto di indossare una tuta in lycra, equipaggiata di unità sensoristiche inerziali (IMU) e, di correre su di un treadmill 4 trial per un periodo di tempo stabilito da protocollo di 5 minuti ognuno, indossando la scarpa Conventional (scarpa A) e quella Maximalist (scarpa B), in un ordine predefinito ABBA. A partire dai dati cinematici relativi agli angoli articolari, ottenuti dai sensori inerziali, una volta implementati in Pyton, è stata valutata attraverso gli Esponenti di Lyapunov e la Sample Entropy la stabilità dinamica locale del ciclo di corsa alla caviglia, ginocchio e anca, poiché una variazione dello spessore dello strato di cushioning costituente la suola della scarpa potrebbe influenzare la traiettoria di corsa stessa.
Infine, una valutazione delle condizioni cinematiche (angolo di flessione anca e ginocchio, dorsi e planti-flessione della caviglia durante la fase di contatto tra la scarpa e il terreno), per entrambe le calzature, è stata fatta nel piano sagittale.

Convenzioni di riferimento adottate nell'analisi

Per descrivere in maniera univoca un movimento nello spazio, è necessario identificare dei riferimenti planari e direzionali standardizzati *(Figura S1)*:

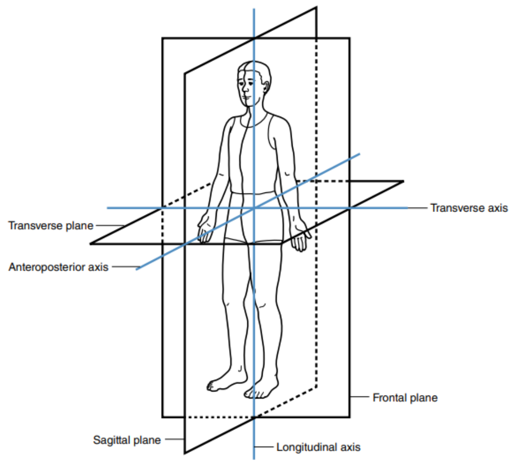

***Figura S1**: Rappresentazione dei piani e delle direzioni convenzionali a descrivere l'anatomia nello spazio.*

"Sagittale", è il piano che divide l'individuo esattamente a metà, identificandone la metà di destra e di sinistra, contenente ognuna un arto superiore e uno inferiore. L'asse di riferimento è quello perpendicolare al piano e denominato "trasverso". Perpendicolarmente invece, piano *"trasverso"* e *"frontale"* suddividono un individuo all'altezza del baricentro in arti superiori e arti inferiori il primo, mentre in parte frontale e parte posteriore il secondo. Gli assi di riferimento sono rispettivamente: l'asse *"longitudinale"* e quello *"anteroposteriore"* [4].

Un focus del progetto focalizzato sull'analisi degli arti inferiori richiede una transizione dei sistemi di riferimento da ordinari a relativi, utili a descrivere con maggiore precisione solamente la componente inferiore del corpo *(Figura S2)*. Nel piano sagittale si considerano *"l'estensione"* e *"la flessione"* sia per l'anca che per il ginocchio; dalla "*posizione anatomica di riferimento"* (posizione verticale in piedi, con gli arti superiori lungo i fianchi, quelli inferiori distesi e i palmi delle mani rivolte verso in avanti) vengono ruotati in senso orario la prima (richiamando il ginocchio al petto), e antiorario il secondo (portando il tallone sotto al gluteo)

per la flessione, mentre esattamente l'opposto per l'estensione. *"L'iperestensione"* invece è il raggiungimento e superamento dell'arto oltre la posizione anatomica di riferimento dell'anca.
La caviglia invece, esegue *"dorsi-flessione"* quando dalla posizione anatomica, avvicina le dita del piede alla tibia, e *"planti-flessione"* quando dalla posizione anatomica la punta del piede viene ruotata in senso orario nel piano sagittale [2].

Nel piano frontale invece, il ginocchio viene spesso modellizzato senza alcun grado di libertà, mentre la caviglia affronta *"un'eversione"* quando la parte laterale della suola si alza e *"inversione",* quando ad alzarsi è la zona interna della suola. Infine l'anca, che sperimenta *"abduzione"* quando dalla posizione anatomica lateralmente l'arto viene allontanato dal baricentro corporeo, e *"adduzione"* quando dalla posizione laterale viene riportato in posizione anatomica [2].

Per ultimo il piano trasverso: anca, ginocchio e caviglia hanno in comune un movimento simile di *"rotazione interna"* e *"rotazione esterna",* rispettivamente una torsione dell'arto inferiore in senso orario e antiorario nel rispetto all'asse longitudinale [2].

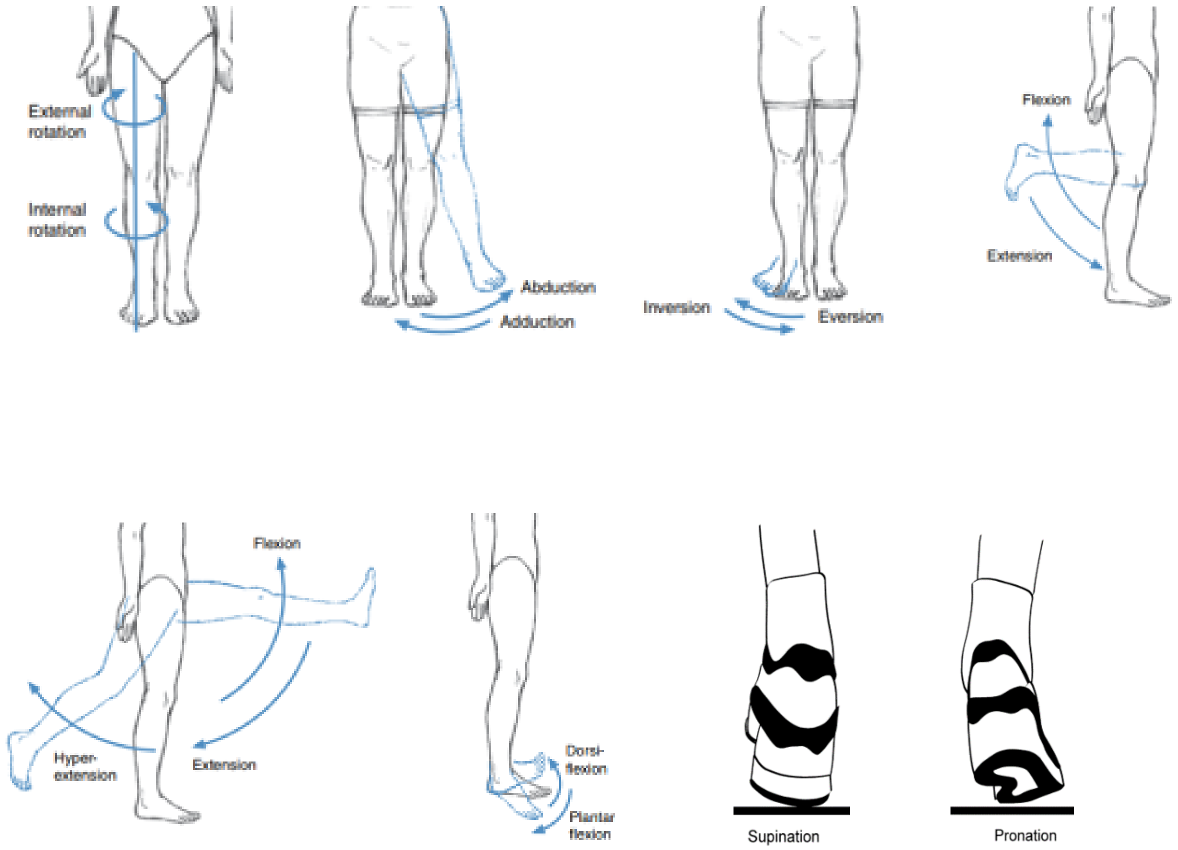

***Figura S2**: Rappresentazione dei diversi movimenti articolari dell'anca, ginocchio e caviglia nei tre piani ordinari.*

La caviglia però, è un'articolazione estremamente complessa, la più complessa tra quelle degli arti inferiori, infatti molte volte combina movimenti su tutti e tre i piani ortogonali contemporaneamente. La combinazione infatti di inversione, planti-flessione e adduzione genera *"supinazione",* mentre eversione, dorsi-flessione e abduzione produce *"pronazione"* [5].

Simultaneamente alla convenzione adottata per identificare i movimenti articolari inferiori nello spazio, è comunque necessario, per misurare con una certa accuratezza i parametri anatomici richiesti a migliorare l'acquisizione e l'analisi dei dati, valutare l'intera struttura anatomica dell'articolazione.

La caviglia è per sua definizione un'articolazione complessa, è suddivisa di fatto in due parti: articolazione talo-crurale e articolazione sub-talare, ognuna con un sistema identificativo di coordinate parziale differenti. Il sistema di riferimento locale dettato dall'unione dei due sistemi, identifica invece i tre assi di riferimento (x, y, Z) come passanti attraverso astragalo, il calcagno ed entrambi i malleoli rispettivamente [6].
L'articolazione del ginocchio invece, composta sempre da due sistemi cartesiani parziali, è però tendenzialmente più semplice della caviglia a causa di un numero minore di gradi di libertà. Il sistema di riferimento locale identifica negli assi X, y, z, quelli passanti per l'epicondilo femorale, il piatto tibiale e l'asse tibiale rispettivamente [7].

Infine, l'articolazione dell'anca, come per tutti i casi composta da due sistemi di riferimento parziali; è la più interna e difficilmente identificabile dall'esterno. La necessità di identificare il centro di rotazione senza analisi invasive identifica la possibilità di assumere come perno di rotazione la posizione del "Gran Trocantere" [6].

Il ciclo di corsa: Fasi e Biomeccanica

Con sviluppo principalmente nel piano sagittale, un ciclo di corsa era inizialmente suddiviso in: *"fase di supporto",* quando almeno un arto inferiore è a contatto con il terreno, e in *"fase di recupero",* quando non c'è alcun contatto tra piedi e terreno. Nonostante la corsa, così come la camminata, siano movimenti innati, non vi è però mai un individuo che ricrei la stessa traiettoria di un altro.

Oggi, in maniera più dettagliata, si seziona la traiettoria di corsa in:

- *"Step": è* la dinamica che intercorre tra il initial contact di un piede e il toe-off dell'altro, è la metà di uno Stride (racchiuso tra due initial contacts ipsilaterali consecutivi). Due parametri descrivono questa dinamica: la *"step frequency (SF)"* e lo *"step lenght (SL)".* Influenzato dallo stile di corsa, SF è linverso della somma tra il tempo di appoggio e quello di volo del piede. Il rapporto SL/SF rappresenta la velocità di locomozione [8].
- *"Stride":* tra un initial contact e quello successivo, ma sempre dello stesso piede, rappresenta un intero ciclo di corsa. Ha una durata temporale variabile, ma non molto diversa da 600 ms. Sono due step consecutivi [8].

- *"Swing Phase":* definita come la dinamica di volo del singolo arto, è il tempo che intercorre tra il toe-off e il successivo foot-strike dello stesso piede. In questa fase l'anca si estende e il ginocchio raggiunge la massima flessione; un susseguirsi di flessione ed estensione riporta il piede a contatto con il terreno [5].
- *"Stance Phase":* dinamica di contatto continuo tra piede e terreno, inizia al foot-strike e termina al toe-off dello stesso piede. Fase in cui articolazioni e muscolatura sono più sollecitati. Parametri ad essa associati sono lo *"stance time",* tempo di appoggio del piede a terra e lo *"stance vertical dispalcement",* la spinta fornita dal contatto con il terreno, definisce un tempo di contatto elevato come meno dispendioso energeticamente, ma al tempo stesso sinonimo di una velocità meno sostenuta [9].

- *"Float phase":* fase di sospensione completa, non c'è alcuna forma di contatto tra i piedi e il terreno. Flessione dell'anca e rotazione del bacino sono le situazioni più frequenti. Complementare alla fase precedente, anche questa è descritta attraverso il *"float or flying time"* e il *"float vertical displacement".* E' racchiuso tra toe off e initial contact controlaterale. Il risultato della forza verticale generata durante la stance phase è l'oscillazione del centro di massa durante la fase di volo; il tempo di oscillazione, che con una durata di 100-150 ms a secondo dell'abilità del runner di generare potenza, è invece il tempo di volo [9].

Fondamentale è la suddivisione in fasi del ciclo di corsa, oltre che molto utile a descrivere in maniera settoriale gli aspetti cinematici quali angoli articolari e accelerazioni di segmenti, che altrimenti sarebbero difficilmente identificabili.

Gli angoli articolari possono essere analizzati in funzione del tempo oppure di un altro angolo articolare. Anca, ginocchio e caviglie sono analizzate separatamente; il ginocchio per esempio, in leggera flessione nel momento in cui il tallone tocca il terreno, raggiunge il 60-65% al termine della fase di appoggio, per distendersi completamente allo stacco dell'ultimo dito. Ritorna così, nuovamente in flessione nella prima parte della fase di volo, per estendersi nuovamente prima che il tallone si appoggi a terra. L'anca invece, è flessa quando in volo, ma in estensione durante la fase di appoggio, quando allineata con il baricentro. La caviglia infine è leggermente abdotta e dorsi-flessa nell'istante dell'impatto a terra, ma in pronazione in procinto di stacco dal terreno.
Due articolazioni *(Figura S3)* a confronto invece, con spostamento relativo l'una all'altra, restituiscono un numero maggiore di informazioni a livello coordinativo. Durante l'impatto del piede con il terreno l'anca è flessa, la caviglia leggermente planti-flessa incrementa leggermente negli istanti successivi e il ginocchio anch'esso flesso, prima di incrementare nella parte centrale di supporto, per successivamente estendersi, anche se non completamente. Nel frattempo, l'anca che era leggermente flessa al foot-strike, inizia subito ad estendersi, seguita poco dopo dalla caviglia che inverte la tendenza in dorsi-flessione nell'ultima parte della fase di supporto. Durante la fase di swing quando entrambe le altre articolazioni si flettono nuovamente e l'anca, anche se più lentamente continua anche dopo la massima flessione del ginocchio, quest'ultimo però raggiunge angoli nettamente superiori all'anca, e la caviglia che termina il ciclo con una nuova planti-flessione di un angolo anche superiore *(Figura S3)* [10, 11].

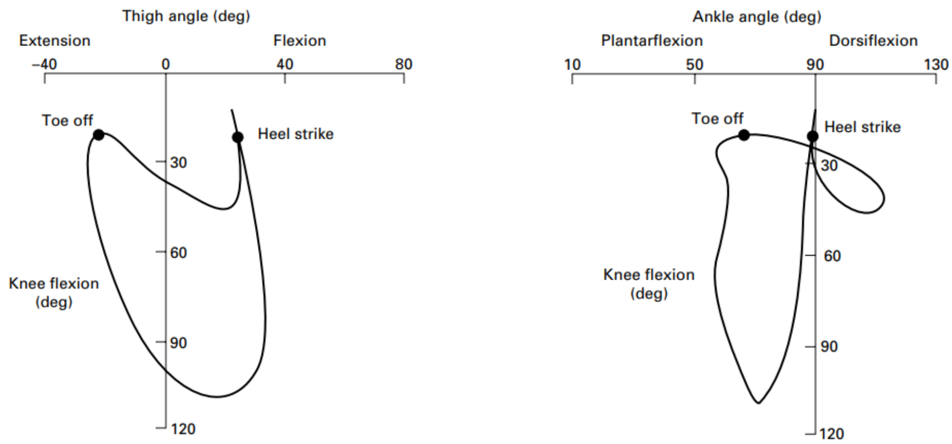

Figura S3*: Rappresentazione della traiettoria di movimento del ginocchio rispetto all'anca/coscia (a sinistra) e del ginocchio rispetto alla caviglia (a destra).*

Oltre alla cinematica che si occupa di descrivere gli spostamenti è anche molto investigata la cinetica che si occupa invece di analizzare le forze che generano gli spostamenti. Questa forza propulsiva è descritta da una *"Distribuzione plantare delle pressioni"* di contatto e dalla *"Forza di reazione con il terreno*" che si propaga lungo tutti i segmenti inferiori accelerandoli.

Un profilo di pressioni plantari che parte dal tallone, raggiunge in soli 60 ms dal primo contatto anche la parte anteriore del piede; servono però 140 ms circa, affinché si sviluppi la maggiore pressione, proprio sulle dita del piede, quasi in corrispondenza del toe-off, riducendo la spinta al solo metatarso e pollice. La reazione del terreno al contatto sviluppa tre componenti della forza: la "*componente medio-laterale"* responsabile del cambio di direzione, la *"componente antero-posteriore*", sempre nella direzione del moto e responsabile di accelerare o frenare i segmenti corporei e infine la *"componente verticale"* che sfida la gravità. Proprio quest'ultima componente a sua volta è divisa in *"impatto"* e in *"propulsione"*; la prima attiva i muscoli in 50 ms preparandoli al contatto del piede con il terreno senza poter più modificare la reazione dopo il contatto stesso, la seconda sviluppata tra i 50 e i 250 ms dal contatto con il terreno, genera lo spostamento del centro di massa; non si deve dimenticare che questi valori sono comunque valori medi. Entrambe le situazioni sono utili a definire l'istante di foot-strike e toe-off quando la forza registrata, ad esempio da una pedana di forza, supera i +20N e i -20N rispettivamente. Impattare il terreno con l'avampiede riduce il picco di forza d'impatto del 35-50% [10].

Scarpe caratteristiche per il Trail-running

Il continuo e rapido sviluppo tecnologico, verificatosi negli ultimi decenni, ha contribuito a lanciare sul mercato una grandissima varietà di calzature, ognuna con una tecnologia leggermente differente dalle altre; dalla lamella in fibra di carbonio integrata tra la suola interna e quella esterna, alla differente geometria svasata nella parte posteriore della suola, una grandissima varietà di esigenze di comfort richieste dal consumatore sono state soddisfatte. Così come accade per tutte le tecniche, in modo particolare per il trail-running, risulta importante raggruppare la vasta scelta in famiglie.
Un piuttosto recente, ma altrettanto significativo raggruppamento è quello di suddividere le scarpe in *"Minimaliste", "Neutrali o Convenzionali"* e "*Massimaliste" (Figura S4).*

❖ Le scarpe minimaliste sono così chiamate a causa della ridotta area di contatto all'interfaccia tra suola e terreno, flessibilità e peso. Ciò che contraddistingue la performance di queste calzature dalle altre però, oltre al ridotto spessore della suola (non superiore ai 10-15 mm) è il dislivello piccolissimo o nullo che c'è tra la parte posteriore e anteriore della scarpa. Proprio quest'ultima caratteristica divide le scarpe minimaliste in due sottogruppi:

- *Barefoot:* il dislivello tra tallone e punta è nullo, lo spessore della suola non superiore ai 10mm e la parte anteriore della scarpa più ampio del tallone, talvolta assumono una posizione precisa come dita.
- *Minimally:* con uno spessore della suola invariato dalla precedente, ma un dislivello tra punta e tallone di 4-8 mm, uno spazio standard per la parte anteriore ma ancora senza un arco plantare definito.

La loro particolare struttura (tallone e punta allo stesso livello) sposta il punto di impatto del piede con il terreno nella parte medio/anteriore, incrementando l'angolo di planti-flessione in tutta la fase di supporto, generando grande controllo e stabilità nel movimento [12].

❖ Le scarpe neutrali o convenzionali, con caratteristiche intermedie, presentano un peso maggiore rispetto alle minimaliste (280-350 g), un dislivello tra la parte posteriore e anteriore del piede sicuramente più elevato (10-12 mm ma anche superiore), uno spazio per le dita che si riduce significativamente causando maggiore deformazione dell'avampiede, ma soprattutto uno spessore della suola di assorbimento dell'impatto tra il piede e il terreno nettamente più elevato e ingombrante rispetto alle calzature precedenti (10-25 mm) [13].

A differenza delle scarpe minimaliste, quest'ultime si presentano con suole più rigide e sono, come già menzionato anche più spesse, un arco plantare più pronunciato, e una resistenza torsionale specialmente nella parte posteriore del piede maggiore, disturbando un po' la stabilità e il controllo del movimento, migliorando però l'assorbimento dello shock di impatto tra il piede e il terreno duro.

❖ Le scarpe massimaliste, contrariamente a quanto si pensi, non necessariamente, a dispetto del loro nome devono essere esattamente l'opposto delle scarpe minimaliste. Proprio per questo, se è vero che lo spessore della suola è molto elevato rispetto alle altre due famiglie (intorno a 30 mm o superiore), molte volte non c'è un dislivello tra il tallone e le dita del piede, esattamente come per le scarpe minimaliste. Uno spessore e rugosità della suola superiore alla scarpa convenzionale, incrementano maggiormente l'assorbimento dell'energia rilasciata dal terreno. Una suola molto grande e dall'aspetto massiccio, nonostante l'incremento di peso, aumenta la resistenza allo scivolamento e la rigidezza della caviglia,

compromettendo leggermente quella del ginocchio che generalmente è più elevata per una scarpa minimalista.
Uno spessore maggiore della suola, specialmente su superfici molto irregolari come quelle per trail-running garantisce una protezione, tenuta e comfort del piede migliori, riducendo la pressione di contatto tra pianta del piede e terreno sia nella parte anteriore ma soprattutto in quella posteriore; sicuramente una miglior attenuazione della forza esercitata sul piede rispetto alla scarpa minimalista e anche convenzionale. Un'attenuazione maggiore si traduce però in un più lento rilascio, che incrementa il tempo di contatto tra piede e terreno, un passo più lungo, ma un rischio infortunio per rottura da stress maggiore. Un rischio più elevato è dettato dal fatto che, nonostante l'energia assorbita incrementi riducendo la fatica e favorendo il risparmio energetico, rimane comunque elevata la pressione di impatto verticale (la forza d'impatto) sulla caviglia che non subisce variazioni.
L'incremento del cushioning all'altezza del tallone, sposta il punto d'impatto del piede con il terreno dalla parte anteriore a quella posteriore [14].

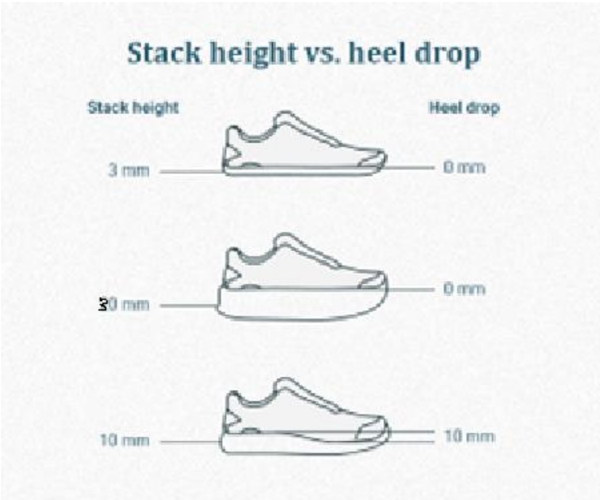

Figura S4: *Rappresentazione delle diverse principali tipologie di scarpe da trail-running sul mercato: Minimaliste (in alto), Massimaliste (al centro) e Convenzionali (in basso).*

La maggior parte delle suole è composta da EVA, una schiuma elastomerica tra le più adatte per assorbire energia, con sufficiente viscosità e rigidezza. Nel corso del tempo, evoluzioni nella composizione, nella geometria e nella microstruttura hanno permesso di migliorarne sia la performance tecnica che la prevenzione di infortuni.

Una suola più spessa può essere meno densa, e se questo è vero, quindi ha un peso minore, purtroppo come schiuma più morbida si degrada più velocemente (prima massimalista e poi quella convenzionale, soprattutto nei punti di maggior appoggio del piede), deformando la suola, ed oltre a ridurne la durabilità mette a rischio infortuni chi le indossa. Soprattutto per quelle calzature in cui il tallone è più alto delle dita, la parte posteriore della scarpa è quella che si degrada per prima, favorendo l'adduzione del ginocchio, una delle principali cause di sindrome femorale patellare, ileo-tibiale, osteoartrite, oltre che problemi lombare e al collo a causa della posizione assunta sbilanciata in avanti [15,16]. D'altro canto, una suola più spessa mitiga l'effetto di una superficie irregolare, favorendo la riduzione di frattura da stress sugli arti inferiori e il recupero da fasciti plantari e overuse che invece possono verificarsi in scarpe minimaliste. Infine, le scarpe minimaliste attivano però in misura maggiore il vasto mediale obliquo che riduce il rischio di infortuni alle ginocchia [17,18,19].
Premesso la categoria di scarpe perfette tra Minimaliste, Neutre e Massimaliste non esista, ogni calzatura è più o meno adatta ad una specifica funzione; la soluzione più semplice per mitigare la perdita di performance e quella di intervenire riducendo la dimensione microstrutturale delle celle chiuse, aggiungendo miscele di poliuretani (in corrispondenza dell'arco plantare), che ne aumentano la densità e quindi la durezza con annessa durabilità.

Le due tipologie di scarpe Adidas® Terrex Speed SG e Altra® Olympus 4 (Convenzionale e Massimalista rispettivamente) usate durante la sperimentazione evidenziano come preannunciabile, una deformabilità maggiore per la scarpa massimalista (17,300 mm) con più cushioning rispetto a quella convenzionale (11,003 mm), che invece con uno spessore minore della suola si deforma meno a parità di carico in compressione applicato. Un test di fatica evidenzia come il ciclo di isteresi sia significativamente maggiore per la scarpa massimalista rispetto a quella neutra (*Figure S5)*; poiché l'area interna al grafico descritto dal ciclo rappresenta l'energia dissipata in forma di calore dalla suola durante l'applicazione del carico, la scarpa massimalista assorbe meglio l'energia scambiata con il terreno, ma è meno performante nella propulsione. D'altra parte invece, la scarpa convenzionale, che presenta una suola più fine, limita l'effetto viscoelastico delle catene polimeriche che raggiungono prima l'equilibrio performando meglio in fase di spinta.

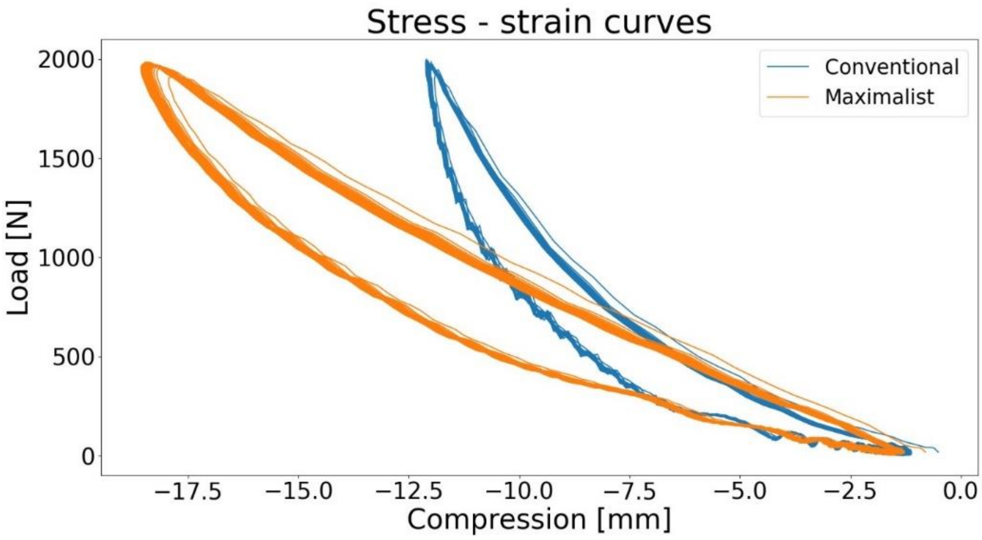

Figura S5: *Rappresentazione grafica forza/spostamento della suola per la scarpa convenzionale (blu) e quella massimalista (arancione);*

Metodologia Sperimentale

A otto partecipanti, maschi, senza infortuni negli ultimi 3 mesi prima dello studio, patologie pregresse e con un volume settimanale di almeno 10km corsi, è stato chiesto di indossare una tuta doppio layer in lycra, estremamente elastica. Un sistema di 17 sensori inerziali (IMU) organizzati in 4 stringhe ognuna di 3 sensori, due per gli arti inferiori e due per quelli inferiori, più testa, sterno, mani e bacino singoli, dispiegati in tutto il corpo secondo una collocazione fissa e brevettata dalla casa produttrice del sistema, è inserito proprio nel doppio strato tissutale utile all'isolamento del sistema dal diretto contatto con la pelle. Attraverso appositi connettori, tutti i dispositivi inerziali sono collegati ad un Body-Pack, che alimentato a batteria trasmette il segnale dei sensori ad un'antenna ricettiva collegata al laptop. Un dispositivo hardware che interfacciato al software: Xsens Analyze®, riproduce a video, in maniera virtuale, i movimenti dell'atleta; proprio attraverso un sistema di XSens 3D Motion Tracking (*Figure S6)*.

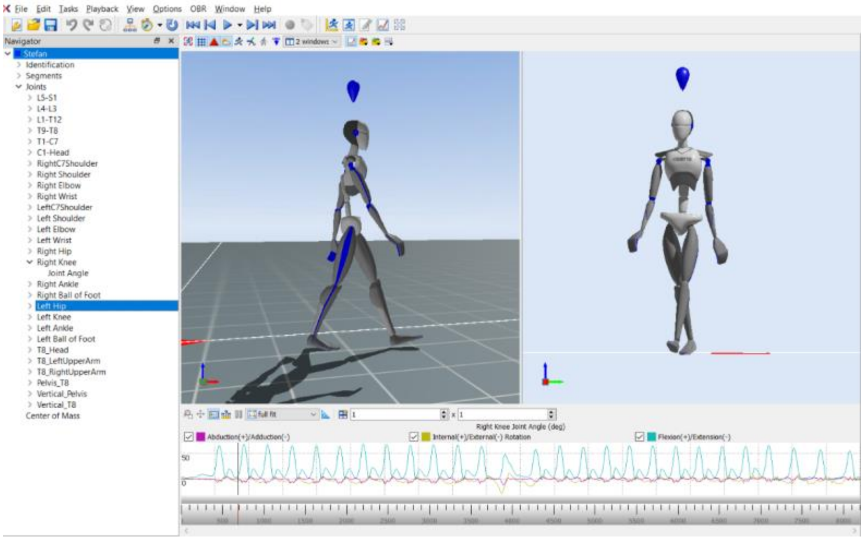

***Figura S6**: Rappresentazione interfaccia grafica del software Xsens Analyze®*

A seguito della vestizione, dopo alcuni istanti di ambientazione e assestamento dei sensori in posizione naturale, si procede con la calibrazione del sistema di cattura del movimento. Indossata la calzatura preliminare, la calibrazione prevede 5 secondi in N-Pose (pozione eretta, arti superiori lungo i fianchi, palmo delle mani rivolto verso i fianchi e piedi paralleli rivolti in avanti), 12 secondi successivi di camminata il più naturale possibile, e ultima fase nuovamente in N-Pose *(Figura S7)* durante l'elaborazione della calibrazione. La procedura calibrativi è necessaria ogni volta che tra una fase e l'altra del test si cambia scarpe.

***Figura S7**: Rappresentazione reale della posizione N-Pose.*

Ultimata la fase di calibrazione, inizia quella di *"Self-selected warm up"*, la fase di avvicinamento e riscaldamento al test vero e proprio, ma ugualmente importante perché identificativa della velocità poi utilizzata durante tutto il test. Il riscaldamento dura tra i 4 e i 10 minuti; partendo da 2,0-2,5 m/s, ogni 10-15 secondi circa, con intervallo costante, si incrementava progressivamente la velocità di 0,1 m/s finché il partecipante sotto suo feedback personale sta correndo ad una velocità sostenuta ma comunque nella sua zona di comfort (uguale a 3 su una scala da 1 a 5, ove 1 significa riscaldarsi a malapena e 5 la massima velocità sostenibile in un test sui 10km). Annotata la velocità raggiunta, si esegue poi lo stesso procedimento (stoppando il treadmill nuovamente una volta raggiunta la zona di comfort) ma in senso opposto, ovverosia partendo da una velocità almeno 0,5 m/s superiore rispetto a quella precedentemente raggiunta, che a mano a mano viene decrementata. Affinché la procedura sia valida, la velocità raggiunta in fase di accelerazione e decelerazione non devono discostarsi di in valore superiore al 10%. Un valore entro quel limite delibera l'inizio

del vero test che ha per velocità il valore medio tra quelli raggiunti, con esito negativo la procedura è da ripetersi.
Considerata la fase di warm up ad esito positivo, ad ogni partecipante verranno fornite le stesse due tipologie di calzature: scarpa A (Conventional) e scarpa B (Maximalist), le due scarpe sulle quali si valuterà l'influenza che esse hanno sulla stabilità, complessità del movimento di corsa. Ogni test consiste di 4 sessioni da 5 minuti di corsa su treadmill, indossando una volta la scarpa A e poi la B, tenendo poi la B e concludendo con la A, in una sequenza ABBA atta a compensare il potenziale bias dovuto all'affaticamento. Come precedentemente precisato, ogni volta che si cambia scarpa è necessaria una nuova calibrazione. Il treadmill elimina le condizioni ambientali, rendendo possibile lo studio degli effetti esclusivamente dovuti alle scarpe.
Acquisiti i dati sperimentali di tutti e 5 i minuti per ogni sessione, vengono da noi tagliati nel minuto centrale e automaticamente filtrati e riprocessati a 240 Hz dal sistema Xsens per la rimozione di eventuale rumore nel segnale. I valori cinematici di ampiezza e accelerazione relativa dei segmenti articolari inferiori, ricavati attraverso i sensori inerziali verranno implementati su script di Pyton a me già forniti.

Approccio attraverso i sistemi dinamici

I sistemi sono definiti *"dinamici"* quando evolvono nel tempo seguendo un percorso ben preciso e deterministico. Un movimento ciclico che si ripete nel tempo, per quanto simile non sarà mai uguale alla ripetizione successiva, bensì presenta una certa variabilità, caratteristica insita in ogni sistema biologico.
Tre Principali teorie descrivono la variabilità: (1) Optimal movement pattern: variabilità come deviazione da uno schema motorio ideale, (2) variabilità come la ridondanza di gradi di libertà di un movimento, e (3) poi c'è *"la Teoria dei Sistemi Dinamici"* che considera la variabilità di un movimento ciclico naturale come l'interazione tra le proprietà di auto-organizzazione del sistema e le condizioni al contorno ove il sistema stesso si trova ad operare, suggerendo una visione della variabilità deterministica anziché stocastica.
Un sistema si definisce deterministico quando conoscendo lo stato iniziale è possibile predire quello futuro. Questo non significa che tutti i cicli siano perfettamente identici e sovrapponibili *(sistema periodico)*, ma come già detto nemmeno stocastico poiché altrimenti imprevedibile e senza una traiettoria che si ripete; un sistema caotico ha una traiettoria ben precisa di movimento, ma questa è variabile nel tempo *(Figura S8)* [20].
Tuttavia, non per forza una traiettoria non ben definita ha l'obbligo di essere anche complesso; infatti un movimento randomico è davvero non prevedibile, ma nulla impedisce che possa essere un movimento molto semplice. Paradossalmente un sistema caotico è più complesso sia di uno periodico che randomico [21].

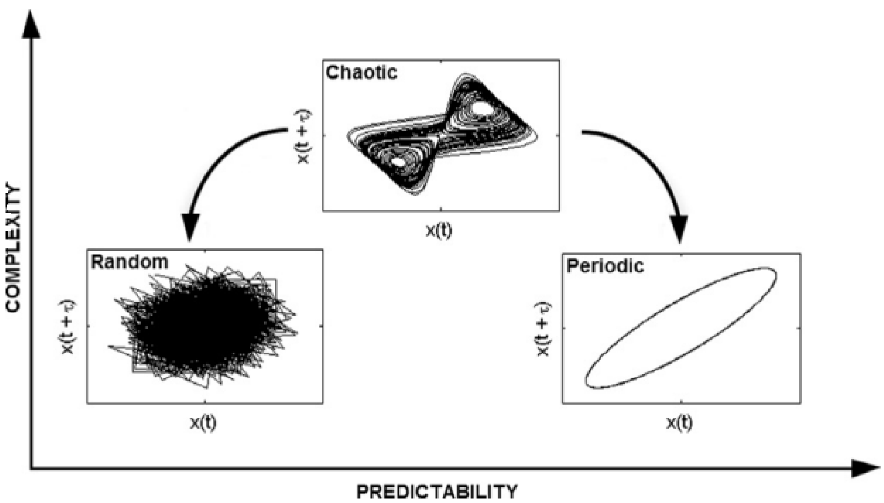

Figura S8*: Rappresentazione della complessità in funzione alla prevedibilità di un sistema caotico, randomico e periodico.*

Per descrivere i sistemi non lineari, sono necessari strumenti che gestiscano sistemi risultati dalla *"Self-organization"* e i *"Constraints"* ma non linearmente tra loro e che operino lontano da una condizione di equilibrio. Proprio i Constraints rappresentano di fatto le condizioni al contorno che limitano e delimitano un sistema. Ogni struttura, come nello specifico la corsa, è condizionato da tre principali tipi di Constraints: di natura esterna ambientale, dovuti alle caratteristiche interne dell'organismo e dettati dalle regole del compito specifico [22].

Esponenti di Lyapunov

Per il calcolo degli esponenti di Lyapunov bisogna, anzitutto, ricostruire il cosiddetto attrattore. Per farlo è necessario rappresentare il segnale (ad esempio un angolo articolare) in funzione di sé stesso ritardato temporalmente. A titolo esemplificativo, basti pensare di avere sull'asse X il segnale s(t) e sull'asse Y il segnale $s(t + \tau)$, dove τ rappresenta il ritardo temporale; in questo caso si hanno due dimensioni, e ogni punto dell' attrattore avrà coordinate $(s(t_i),s(t_i + \tau))$ dove i rappresenta l'i-esimo punto dell' attrattore
Il ritardo temporale ottimale è ottenuto grazie alla tecnica dell' *"Agerage Mutual Information"*, mentre il numero di dimensioni ottimale è ottenuto per mezzo della tecnica del *"False Nearest Neighbour"*.

$$d(t) = De^{t*\lambda}$$

Con D (distanza iniziale tra i due punti considerati), d(t) distanza tra i due punti ad un certo istante temporale successivo e λ esponente di Lyapunov. calcolato mediante l' algoritmo *"Rosenstein Algorithm"* [24,25] e infine LyE (λ) è calcolato come la pendenza della curva costruita sulle divergenze tra i due primi vicini, tutto integrato su metà ciclo di corsa:

$$Y(i) = \frac{1}{\Delta t} \langle ln[d_j(i)] \rangle$$

Gli esponenti di Lyapunov sono un potente strumento, utile per valutare la stabilità locale di una traiettoria, come ad esempio la corsa. Descrivono quanto velocemente due traiettorie discrete vicine l' una all'altradi uno stesso movimento divergono. Più i punti ravvicinati delle due traiettorie considerate divergono velocemente, tanto meno è stabile il movimento.
Definito come la pendenza media del logaritmo della divergenza tra le due traiettorie nello stato degli spazi, LyE è un parametro puramente matematico.
Tanto più è grande il valore degli Esponenti di Lyapunov maggiore sarà la velocità di divergenza e di conseguenza tanto più instabile la traiettoria del ciclo di corsa *(Figure S9)* [23].

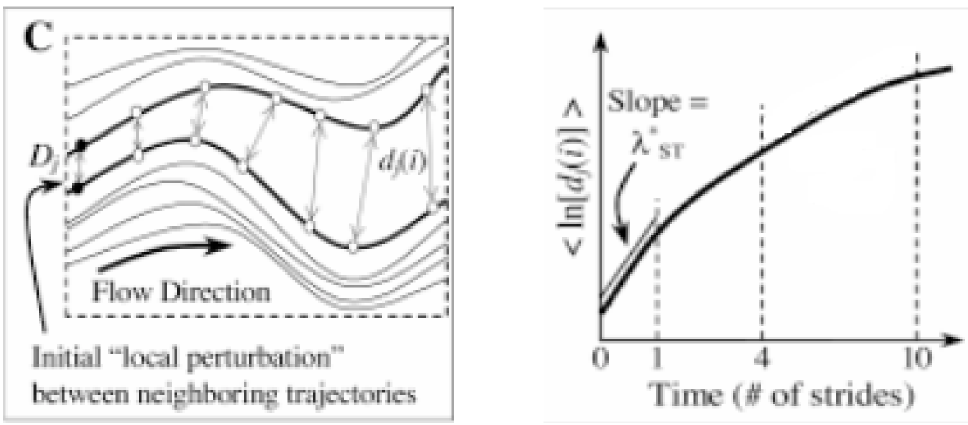

Figura S9: *Rappresentazione grafica del concetto matematico di LyE, con la divergenza della traiettoria (a sinistra) e la pendenza della retta (a destra)*

Sample Entropy

Altro strumento di analisi non lineare è la Sample Entropy. Utilizzata sia per i sistemi stocastici che deterministici, è specifica per valutare complessità e natura stocastica, quindi prevedibilità e regolarità della traiettoria degli arti inferiori durante la corsa quantificandole. Del tutto simile all'approccio precedente, anche questo è puramente matematico, ma a differenza degli Esponenti di Lyapunov è un modello perfezionato nel tempo, che nasce dalla correzione in alcuni aspetti della più nota *"Approximate Entropy"*.

Mentre l'Approximate Entropy è influenzata dalla lunghezza temporale e quindi dal numero di dati acquisiti durante la misurazione, oltre che alla dipendenza dal segnale di rumore di fondo, la Sample Entropy non risente di queste variabili [26].

La Sample Entropy è il valore negativo del logaritmo della probabilità condizionale che in una serie temporale un sottogruppo di m ed m+1 data points si ripeta simile abbastanza a se stesso (data una certa soglia stabilita a priori)Tanto più piccolo è il valore di SampEn quanto più regolare è la traiettoria del ciclo di corsa, mentre maggiore è la natura stocastica del movimento quanto maggiore è il valore di Sample Entropy. In ogni caso, la SampEn è sempre un valore positivo o tal più nullo solitamente compresa tra 0 e 2 [23,28,29].

Prima di tutto è necessario creare due vettori modello: uno costituito dagli "m" elementi di riferimento e l'altro invece costituito dai punti "m+1":

$$\begin{aligned} B^m(r) &= \frac{1}{N-m}\sum_{i=1}^{N-m} B_i^m(r) \\ &= \frac{1}{N-m-1}\frac{1}{N-m}\sum_{i=1}^{N-m}\sum_{j=1,j\neq i}^{N-m}[\text{number of times that } d[|x_m(j)-x_m(i)|]<r] \end{aligned}$$

$$\begin{aligned} A^m(r) &= \frac{1}{N-m}\sum_{i=1}^{N-m} A_i^m(r) \\ &= \frac{1}{N-m-1}\frac{1}{N-m}\sum_{i=1}^{N-m}\sum_{j=1,j\neq i}^{N-m}[\text{number of times that } d[|x_{m+1}(j)-x_{m+1}(i)|]<r] \end{aligned}$$

Per come è stata definita prima, la Sample Entropy dovrebbe essere valutata su un numero infinito di valori, difficili però da ottenere, è sufficiente avere un numero di punti sufficiente, che se raggiunto approssima come infinito:

$$\mathrm{SampEn}(m,r) = \lim_{N\to\infty}\{-\log[A^m(r)/B^m(r)]\}$$

$$\downarrow$$

$$\mathrm{SampEn}(m,r,N) = -\log[A^m(r)/B^m(r)]$$

$$\downarrow$$

$$SampEn(m,r,N) = -\log\frac{\sum_{i=1}^{N-m}\sum_{j=1,j\neq i}^{N-m}[\text{number of times that } d[|x_{m+1}(j)-x_{m+1}(i)|]<r]}{\sum_{i=1}^{N-m}\sum_{j=1,j\neq i}^{N-m}[\text{number of times that } d[|x_m(j)-x_m(i)|]<r]}$$

Risultati

Dall'analisi dei risultati sugli Esponenti di Lyapunov si osserva che la caviglia ha valore medio considerando entrambe le scarpe conventional e maximalist rispettivamente di 1,62±0,30 e 1,78±0,24; nonostante la sua elevatissima complessità, presenta una buona stabilità di movimento. Il ginocchio invece, nonostante nel piano frontale non presenti libertà di movimento, sperimenta per entrambe le tipologie di scarpe coefficiente di LyE 3,05±0,16 per la conventional e 3,24±0,24 per la maximalist, e quindi un'instabilità o variabilità piuttosto elevata nella ripetizione del ciclo di corsa. Per l'anca infine i valor medi di LyE sono 2,84±0,34 e 2,67±0,32 per la scarpa convenzionale e quella massimalista rispettivamente.

Osservato quindi il diverso comportamento generale degli arti inferiori, l'attenzione si è poi spostata sull'influenza, sempre che ci fosse, di due scarpe nettamente diverse tra di loro (Conventional e Maximalist) sulle articolazioni inferiori durante la traiettoria di corsa. Solamente al ginocchio si è potuto osservare un'influenza significativa ($p<0,05$), infatti la scarpa Massimalista infonde maggiore variabilità al movimento rispetto alla scarpa Convenzionale. Lo stesso trend è confermato anche dalla caviglia, che malgrado la non significatività, seppur molto vicina, ($p =0,07$) ricalca una spiccata instabilità sempre per la scarpa Maximalist rispetto a quella Conventional. Infine l'anca, su di essa non si può esprimere nessuna considerazione. Non solo non risulta presente alcuna differenza significativa tra le due tipologie di scarpa, ma nemmeno un trend che le distingua *(Figure S10)*. La significatività delle differenze venne valutata attraverso il test statistico di Wilcoxcon.

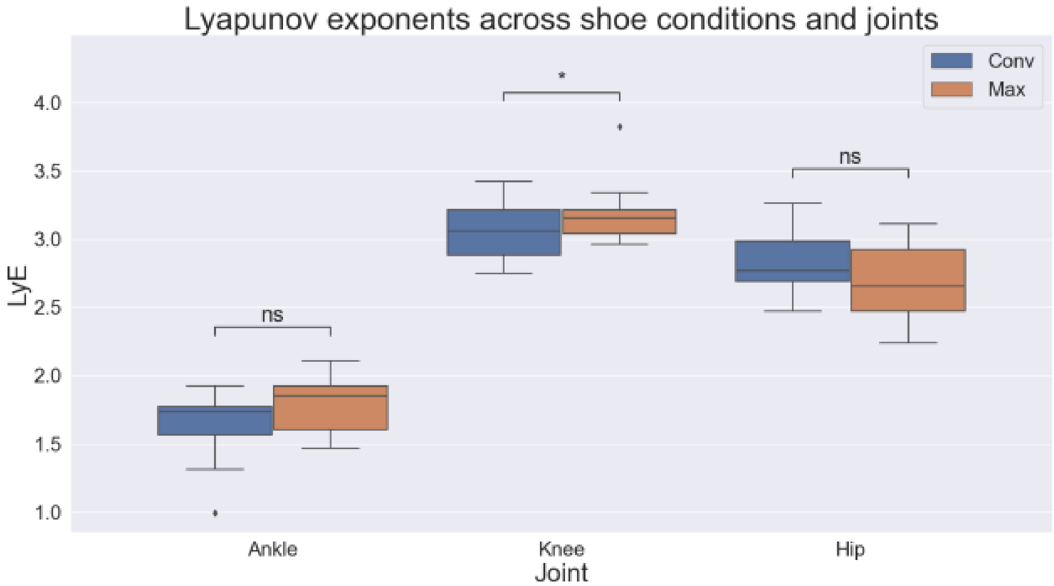

Figura S10: *Rappresentazione grafica degli Esponenti di Lyapunov in funzione al tipo di scarpa indossata e all'articolazione considerata.*

Analizzando successivamente i risultati della Sample Entropy, ed essendo essa un indice della complessità del movimento, si può osservare come in questo caso sia l'anca, tra le tre articolazioni, ad essere quella con un minor valore di SampEn (valore medio di 0,13±0,01 e 0,13±0,02 per entrambe le scarpe). È l'articolazione con il movimento meno complesso tra le tre, quella che, nonostante il movimento più simil-stocastico, presenta la maggiore self-similarity rispetto a ginocchio e caviglia. Anche per la Sample Entropy, così come per gli Esponenti di Lyapunov, il ginocchio presenta invece il valore maggiore (valore medio 0,21±0,01 per entrambe le scarpe). Una complessità del movimento che, anche se di poco, è superiore alla caviglia (valore medio 0,17±0,05 e 0,18±0,06 per la conventional e maximalist rispettivamente), bensì quest'ultima sia più articolata. Attenzione però, che per quanto la complessità tra i diversi punti sembri elevata, contrariamente a quanto accadeva per la stabilità, la SampEn varia in un range più ristretto.

Considerato quindi il diverso comportamento generale degli arti inferiori, l'attenzione si è poi spostata sull'influenza di due scarpe nettamente diverse tra di loro (Conventional e Maximalist) su una possibile variazione di complessità del movimento ciclico di corsa. Malgrado la diversa complessità di base, non è possibile in nessuna delle tre articolazioni (anca, ginocchio e caviglia) riscontrare una significativa influenza della scarpa Massimalista o Convenzionale sulla complessità della traiettoria di corsa *(Figura S11)*.

Una questione molto dibattuta in letteratura riguarda la possibilità che il segnale grezzo, ottenuto dalla misurazione, e filtrato possa o meno influenzare il valore finale di Sample Entropy. Non è chiaro se il segnale mostrato in seguito alla filtrazione abbia un numero di informazioni utili sufficienti ad ottenere differenze di SampEn significative. Utilizzando il Software di Xsens i dati erano già filtrati, e quindi da noi non controllabili. Traiettorie molto lisce quelle ottenute in questo studio, lasciano presagire che la filtrazione dei dati, di fatto abbia un'enorme influenza sui risultati, dal momento che tra le due scarpe A e B la SampEn è praticamente uguale. Anche in questo caso l'analisi statistica è stata valutata attraverso il test di Wilcoxcon.

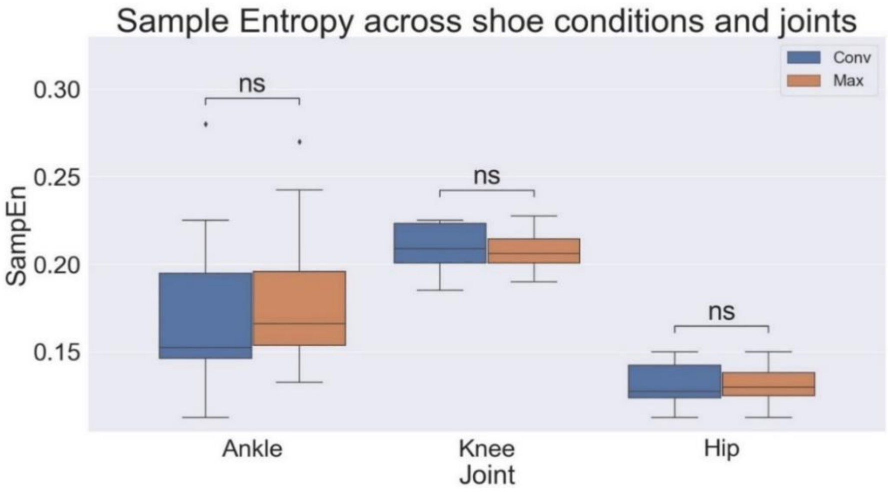

Figura S11: *Rappresentazione grafica della Sample Entropy in funzione al tipo di scarpa indossata e all'articolazione considerata.*

Da un punto di vista puramente empirico invece *(Figura S12)* attraverso alcune immagini è possibile osservare come la scarpa Maximalist, con l'aiuto di un angolo di sfasamento della suola maggiore rispetto ad una Conventional, soprattutto nella parte posteriore del piede, mitighi l'effetto di pronazione, inversione ed eversione del piede. L'effetto appena descritto è stato valutato durante la fase di appoggio, nel momento in cui il tallone si stacca dal terreno. Nonostante il diverso comportamento, l'articolazione della caviglia e del ginocchio presentano comunque un trend di stabilità maggiore con la scarpa neutra, indice del fatto che il fenomeno di pronazione e inversione non è direttamente correlato alla instabilità del movimento circolare.

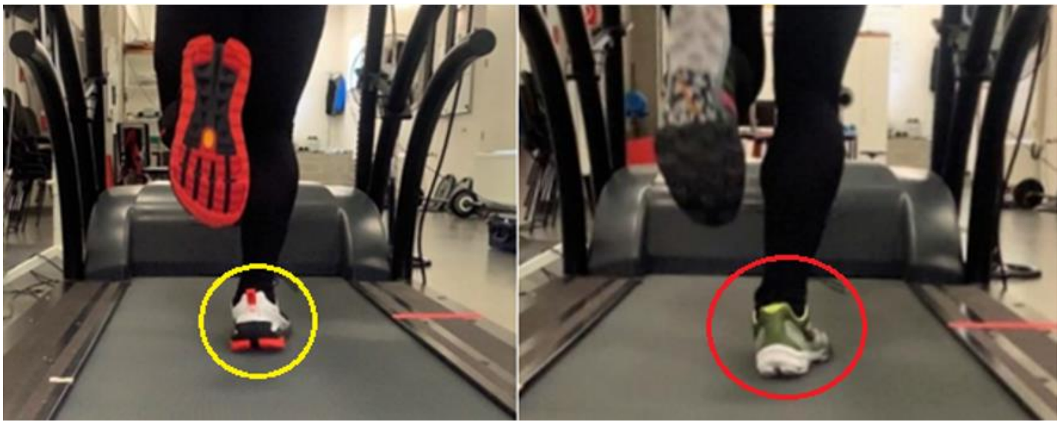

Figura S12*: rappresentazione del comportamento della caviglia durante il ciclo di corsa quando il tallone, durante la fase di appoggio si stacca da terra.*

Gli angoli di flessione ed estensione del ginocchio e dell'anca non sono influenzati dal modello di scarpa indossato; l'alternanza nell'utilizzo di entrambe le calzature (A e B) non crea andamenti significativamente dissimili in nessuna fase del ciclo di corsa; essi sono pressoché sovrapponibili. Gli angoli di dorsi- e planti-flessione della caviglia invece, sono nettamente condizionati dalla scarpa indossata *(Figura S12)*. Anche in questo caso sempre in modo empirico e su di un solo campione (bisognerebbe considerarli tutti), contrariamente a quanto ci si aspettasse, il contatto del piede con il terreno è in posizione maggiormente dorsi-flessa per la scarpa tradizionale rispetto a quella massimalista. Ciò potrebbe essere dovuto al maggior spessore della suola e al maggior peso della scarpa massimalista. Dorsi-flessione incrementa durante la fase centrale di appoggio sia per la Max. che la Conv. rispettivamente. Prossimo al toe-off, si osserva la maggiore plantiflessione durante tutta la fase di volo *(Figure S13)*.

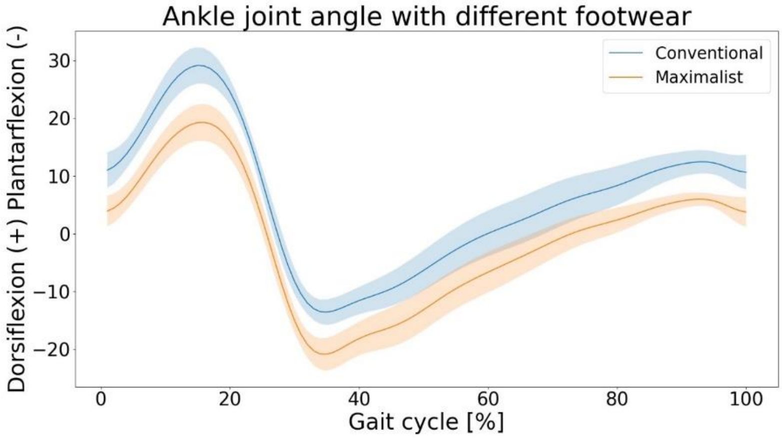

Figura S13: *Rappresentazione dell'angolo articolare in funzione della tipologia di scarpa per un intero ciclo di corsa*

Discussione e conclusioni

Come precedentemente espresso, in maniera significativa per il ginocchio e non completamente significativa ma con un forte trend per la caviglia, la scarpa con una suola più fine e un dislivello tra tallone e punta minore (Coventional) sono più stabili durante l'attività di corsa. Una variabilità della traiettoria maggiore con la scarpa maximalist può essere dovuta ad uno spessore della suola più elevato, che significa più morbida perché meno densa, il quale permette movimenti maggiori e meno controllabili durante la fase di appoggio. A parte una degradazione maggiore, densità più basse sviluppano a parità di carico una maggiore deformazione della suola; essendo essa di natura polimerica con comportamento viscoelastico, una sollecitazione ciclica a fatica genera isteresi più marcata in una suola più spessa dove le catene polimeriche sono in numero più elevato rispetto ad una suola più sottile, necessitando di un tempo maggiore per trovare, dopo una deformazione, il nuovo equilibrio. Una concatenazione di fattori così ampia potrebbe generare un movimento, come summenzionato, meno facilmente controllabile sia sull'articolazione del ginocchio che della caviglia, senza di fatto interessare l'anca, l' articolazione più distante dalla scarpa. Non è da sottovalutare inoltre che una scarpa maximalist sia nettamente più ingombrante e pesante, 330g contro i 225g circa, rispetto ad una scarpa neutra; dettagli da non sottovalutare e che potrebbero influenzare l'atleta, rendendo più complicato il controllo della traiettoria di corsa e quindi più instabile il movimento sia del ginocchio che della caviglia. Benchè un maggiore angolo di svasamento della suola protegga il piede da pronazione e inversione, si osserva comunque un'influenza negativa sulla biomeccanica di corsa. Da un punto di vista della cinematica, gli angoli di flessione ed estensione del ginocchio e dell'anca non sembrano condizionati dal modello di scarpa utilizzato; mediati forse dall'articolazione della caviglia hanno un andamento sovrapponibile per l'intero passo di corsa. L'articolazione della caviglia invece, varia significativamente da una scarpa all'altra sia in condizione di dorsi-flessione che di plantiflessione.

L'articolazione della caviglia ha sempre ricevuto un'attenzione particolare rispetto alle altre, perché considerata forse direttamente connessa alla calzatura, non è ora quella principale; il ginocchio invece, che sembrava poter essere solo un ponte di inversione del trend di instabilità tra l'anca e la caviglia, è l'unico ad essere significativamente influenzato.

Rimangono comunque delle limitazioni in questo studio: il treadmill non rappresenta il terreno di maggiore utilizzo della calzatura in questione, un tempo per familiarizzare con le scarpe troppo corto e il ristretto campione analizzabile a causa dell'unica taglia disponibile 8.5/42, escludendo di fatto la possibilità di testare atlete donne. Ovviando a queste considerazioni, possibili investigazioni future potrebbero considerare più approfonditamente la possibilità di una diretta influenza della pronazione, planti-flessione e inversione sulla stabilità e complessità del movimento ciclico della corsa. In conclusione, molte volte intervenendo dall'esterno su di un sistema come l'organismo umano si possono creare delle instabilità coordinative che normalmente per sua natura, sempre alla ricerca di una condizione di equilibrio, ovvero la massima stabilità possibile non esistono. In questo studio si è visto come due scarpe che differiscono per geometria, deformazione e reazione anche muscolare all'impatto con il terreno, allo spessore della suola intermedia, la dorsi- e planti- flessione e inversione della caviglia possano compromettere le caratteristiche del ciclo di corsa degli arti inferiori in toto.

Chapter 1

General Biomechanics

In this chapter, we will first give an introduction to biomechanics in general before diving into biomechanics of running. In order to understand the patterns of movement of the human body described by biomechanics, it is necessary to look at existing conventional movements in space, anatomical structures and mechanics models.

1.1 Introduction to Biomechanics

Biomechanics is one of the six branches that, together with "Exercise physiology", "motor development", "motor learning", "pedagogy" and "psychosocial", form a science known as kinesiology [1].

The word biomechanics can be divided into two parts: the prefix *"bio-"* and the root *"mechanics"*. The prefix *"bio-"* indicates that this particular science is directly related to a biological system or more generally to living things. *"Mechanics",* as the root of the compound word, represents those biomechanics is directly related to the analysis of forces and their effects; mechanics is a discipline of physics that deals with the account of motion and how forces produce motion.

Accordingly, biomechanics is defined as *"the study of forces (both internal and external forces, acting upon, within, and produced by systems) and their effects (acceleration and deformation) on living systems"* [1].

Forces are more difficult to define than effects because they are more difficult to observe. They are an abstract concept, so forces are usually expressed in terms of their effects.

"When an object starts to move (accelerate) or change its velocity or direction of movement or when an object is deformed, a force is acting upon it" [1].

Biological systems, as mentioned earlier, are usually known as "living systems" and include both plants and animals. Therefore, it is necessary to focus on the biomechanics of animals and especially on the human system when the main topic of research is human biomechanics. The biological part of human biomechanics is composed of three main systems of our body: the skeletal system, the muscular system and the nervous system *(Figure 1.1).*

Human biomechanics analyses mechanical factors in humans and provides key conceptual and mathematical information about the most effective and healthy movement patterns, associated exercises and equipment to improve movements.

When movements and exercises are closely related to sport, the specific branch of biomechanics is called "sport and exercise biomechanics". One of its main focuses is on improving athletes' performance, accelerated learning of new skills and help in diagnosing the causes of injury and its treatments [1,2,29].

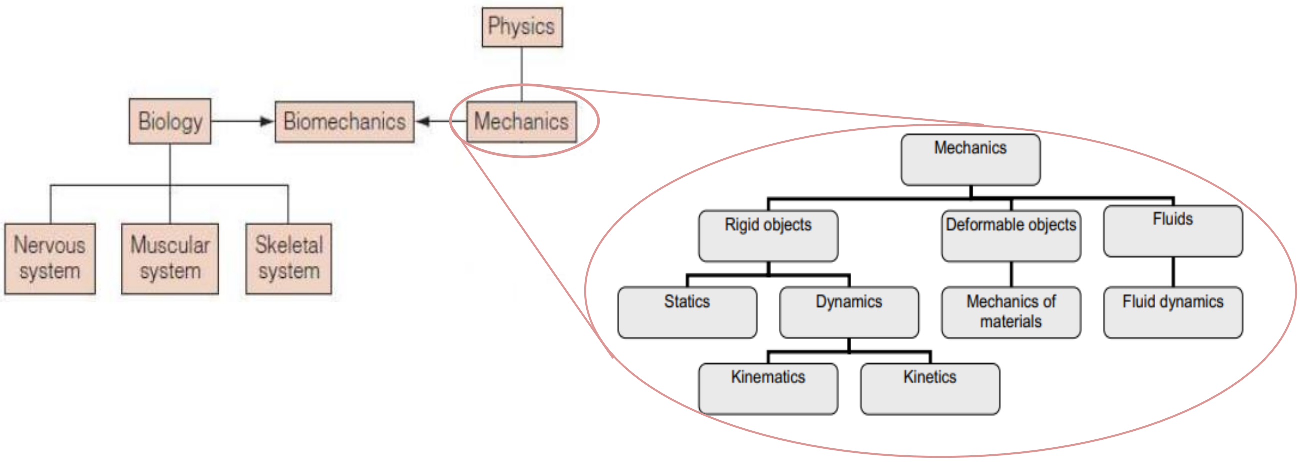

Figure 1.1: *The different branches of mechanics and biomechanics.*

1.2 Mechanics Models in Biomechanics

The study of physics through the science of mechanics is divided into many different areas, each described with a specific model. However, the most important ones for biomechanics are known as "Rigid Body", "Deformable Body" and "Fluid". Deformable body mechanics studies how forces are distributed inside materials and explores the possible causes of damage at many different levels (from cell to tissue/organ/system), while fluid models study the forces that develop in liquids or gases. These branches of biomechanics are used when the body or parts of it are in direct contact with a fluid (heart valves, swimming or sports equipment) to minimise drag.

To study the mechanics of a complex reality, one needs a suitable model that is complex enough to predict the correct action of forces, but simple enough to allow the application of mathematics.

The model most commonly used to describe and explain all movements of people in sport and exercise is "rigid-body mechanics". Deformation (bending, stretching or compression) is considered too small and is therefore neglected. This is especially true for materials, so that this limitation can be considered valid for most studies of the most important segments of our body. This type of modelling and these mathematical assumptions work without a great loss of accuracy of the final result [30].

Furthermore, rigid-body mechanics is further divided into *"statics"* and *"dynamics"*. Statics studies systems that are in a constant state of motion, at rest or moving at a constant velocity, so that the forces acting on them balance each other. Dynamics studies systems that are in motion and undergo acceleration. In last stance, dynamics can be divided into *"kinetics"* and *"kinematics"*. Kinetics examines internal and external forces that act on systems and cause changes in movement. Kinematics describes only the motion of systems (time, velocity, trajectory, acceleration and displacement), usually the pattern or technology of the motion. The technologies used in kinetics are force platform, pressure sensors and force sensors, while kinematics usually uses video cameras, accelerometers, electro-goniometers and inertial sensors (which were also used for this study) [29,31,32].

In summary, most biomechanical aspects in humans are based on the analysis of the skeletal system for the biological part and the dynamics for the mechanics' part.

When using the rigid body model, each segment of the human body is considered to be extremely rigid and connected by joints in a kinetic chain. A kinetic chain is the representation of body segments connected by joints and moving in space with a specific configuration. A kinetic chain can be ***"open", "closed"*** and

"functional" (the combination of open and closed chain in the same system) depending on the interaction between body segments and the ground or objects in the surrounding space. It is the functional chain that represents the walking movements as accurately as possible. In fact, some limbs are involved in open-chain movement (e.g., the foot swinging freely in the air) and others in closed-chain movement (the foot in contact with the ground).

However, human movement can be represented by segmented movement patterns, which are usually very complex. They are called ***"General Movement"*** and are a combination of linear (straight line and curved translation) and angular movement. This makes it necessary to break down the structure during a biomechanical analysis in order to use mathematical tools to describe the movements *(Figure 1.2)* [2]. Angular motion is more commonly used than linear motion because most human movements are the result of rotation of limbs around joints

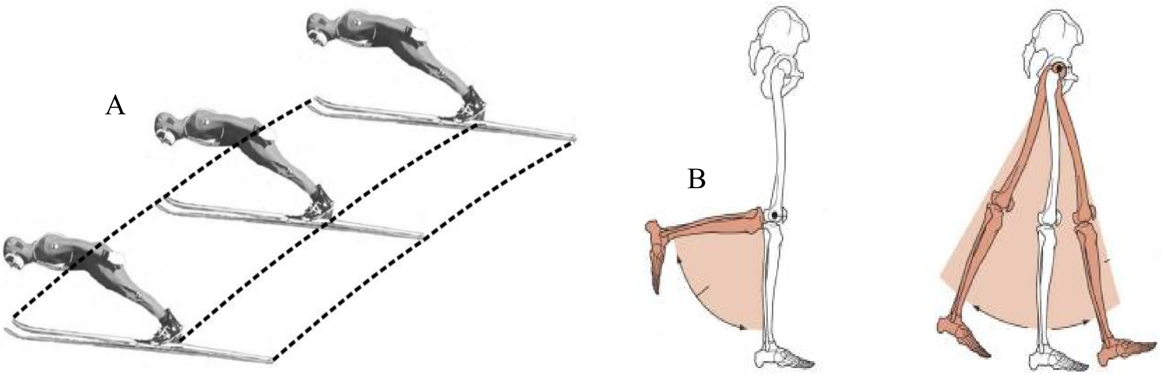

Figure 1.2: *A possible linear motion (translation) of body (A) and angular motion of bodies joints (B).*

1.3 Reference Planes and Axes in Anatomy

Before describing body movements, it is necessary to set a conventional tri-dimensional space system in which movements take place. Then, 3D space is divided into planes that are perpendicular; combined they are enough to describe all the space *(Figure 1.3)*:

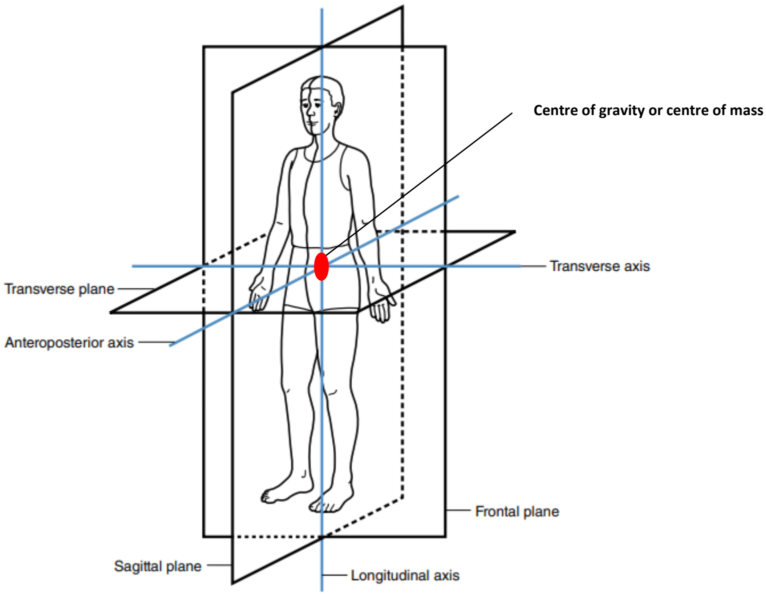

Figure 1.3: *Conventional anatomical planes and axes.*

The three main planes are generally called ***“cardinal planes”*** as they have the cardinal point of the body in common, the centre of gravity or centre of mass. The greatest worth for these planes is describing movements particularly for this study of limb movements. Cardinal planes are [4]:

- ***“Sagittal plane”:*** also called anteroposterior plane, it is vertical and divides the body in half along the midline into right and left masses, most of running movements take place in this plane.
- ***“Frontal plane”:*** also called coronal or lateral plane, it is again vertical, but it divides the body in half along the midline into anterior and posterior masses.
- ***“Transverse plane”:*** also called horizontal plane, it runs through the body horizontally dividing the body into superior and inferior side.

Planes are important to describe limb movements, that can but do not necessarily take place in a cardinal plane (oblique or diagonal) thanks to a combination of them. Most of the time, segments experience a rotation, so rotations occur around specific axes, parallel to those obtained by the intersection of cardinal planes, called ***“anatomical axes”*** *(Figure 1.3)*. They are used to describe angular movement and as for the planes, there is also three of them:

- ***“Transverse axis”:*** also called mediolateral axis, is horizontal and perpendicular to the sagittal plane.
- ***“Anteroposterior axis”:*** also called sagittal axis, is horizontal and perpendicular to frontal plane.
- ***“Longitudinal axis”:*** also called supero-inferior axis, is vertical and perpendicular to transverse plane.

However, for every cartesian system, it is necessary to use a common standard reference point for describing the absolute locations, positions, movements of limbs or other anatomical structures. The most common reference position used for the human body is the so-called ***“anatomical position”*** *(Figure 1.3)*. The body is in an anatomical position when it is standing erect, facing forward, arms and hands are below the shoulders beside the chest. The fingers are completely extended and palms facing forward. Additionally, sport biomechanics normally sets up a protocol in which the full extension of most of the joints is fixed at 0° and the angle increases during joint flexion [33,34].

1.4 Possible Body Movements

1.4.1 Role of Upper Extremities and Torso

During walking, running, or any movement, the entire body plays a coordinative role, not just the lower or upper extremities are necessary. In particular, the ***“torso”*** and the ***“upper extremities”*** have an important influence on limiting injuries and increasing performance.
The torso with its stable and strong muscles ensures stability of the movements of the lower extremity. The “core” muscles are fundamental to absorbing and handing out impact forces and controlling the efficiency of body movements. Also, during the main movement of the torso, ***rotation*** of the muscles of the thorax keeps the spine and the abdomen stable around the axis of the vertebrae [5].

The upper extremities also play a role in balancing and providing stability in motion. Arms are important because each movement counterbalances the opposite leg, in particular during the swing phase of running or walking. They are used to balance the torso as well. During their movement, they help the propulsion of the legs with more efficiency reducing the energy waste. However, an excessive crossover movement of the arms is a signal of lack in stability of the lower body, while a good synchrony between legs and arms minimizes twisting of torso and pelvis, decreases the rotation of torso and head and saves energy.

Albeit the great importance of the upper extremities and the torso for movement, this study will focus on the lower extremities, also called legs, and their movement during a running gait cycle. In order to correctly describe and understand a running cycle, it is necessary to fix some standard movements in the 3-D space [2].

1.4.2 Lower Extremities in the Sagittal Plane

Hip and knee joint movements in the sagittal plane are usually known as ***flexion***, ***extension*** and ***hyperextension*** *(Figure 1.4)*. From the anatomical point of view, flexion is a bending movement around the transverse axis. The joint always acts about the transverse axis. A return of the limb from the bending position to the anatomical position is called extension. Hyperextension is the joint acting on the transverse axis that is a continuation of the extension beyond the anatomical position. The value of joint movement for the hip is quantified as the relative position between the lengthening of the trunk segment (one segment is enough to approximate the trunk because usually very small motions are experienced at the intervertebral joints) and the thigh segment, considering 0° for the anatomical position of segments. Taking into account the grater trochanter crossed by the transverse axis, it can be considered the centre of rotation and joint for the hip. On the other hand, for the knee, the entity of joint movement is obtained by measuring the relative angle between shank and thigh lengthening. Considering the anatomical position of segment as 0°, rotating also in this case around the transverse axes passing through the lateral epicondyle of the femur always crossed by transverse axis is considered the centre of rotation and joint for knee. Additionally, ***dorsiflexion*** and ***plantarflexion*** *(Figure 1.4)* are joint actions characteristic for ankles in the sagittal plane. The first one, around the transversal axis, occurs when the foot is moved forward and upward toward the leg (lifts the toes off the ground and puts the weight on the heels), while plantarflexion occurs when the foot moves downward. The range movement of the ankle during motion is evaluated as the angle between the shank segment and a segment which connects the head of the fifth metatarsal and an artificial point in the heel. Reference position, in this case, considers the foot segment and the shank segment oriented at 90°, though for measurement this angle is set as 0° [2,5].

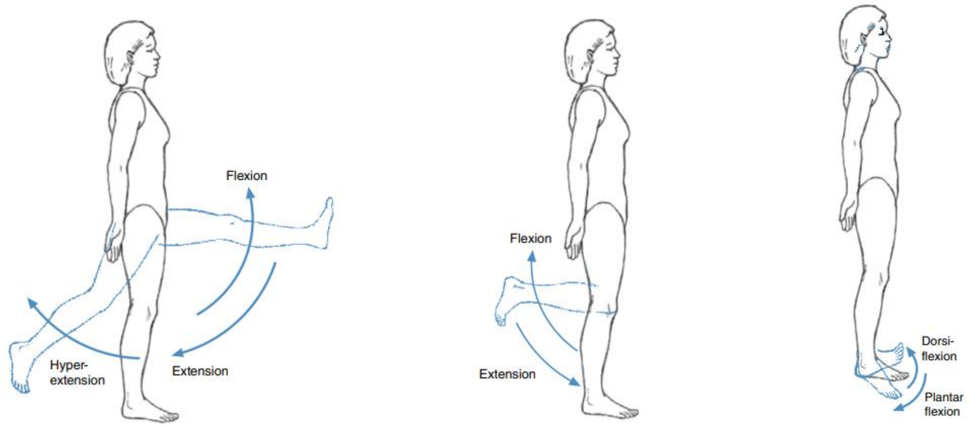

Figure 1.4: *Representation of lower extremities movements in the sagittal plane.*

1.4.3 Lower extremities in frontal plane

Hip joint movements in the frontal plane are usually know as ***abduction*** and ***adduction*** *(Figure 1.5)*. They rotate around the anteroposterior axis. Abduction is the joint movement associated to the largest range of motion, while adduction is responsible for the movement in opposite direction, bringing the limb back towards the anatomical position. The ankle movements in the frontal plane are called ***inversion*** and ***eversion*** *(Figure 1.5)***.** Inversion is when the mid sole is rise, while it is in eversion motion that the lateral sole is lifted. Knee rotation in the frontal plane is considered irrelevant and therefore not counted as a degree of freedom [2].

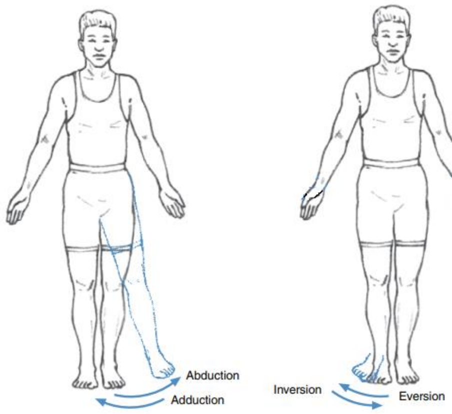

Figure 1.5: *Representation of lower extremities movements in the frontal plane.*

1.4.4 Lower Extremities in the Transverse Plane

Hip movements in the transverse plane are usually known as ***"internal rotation"*** and ***"external rotation"*** ***(****Figure 1.6)***.** The hip rotates around the longitudinal axes. Starting from the anatomical position, internal rotation is the joint actions in which the knees turn inward toward each other, while external rotation is the opposite motion bringing the rotated knee back the anatomical position again. ***"Horizontal abduction"*** and ***"horizontal adduction"*** *(Figure 1.6)* are joint movements that do not start from the anatomical position. Horizontal abduction is the movement of the leg in the transverse plane around a longitudinal axis, moving the leg away from the midline of the body. The opposite movement is called horizontal adduction [2].

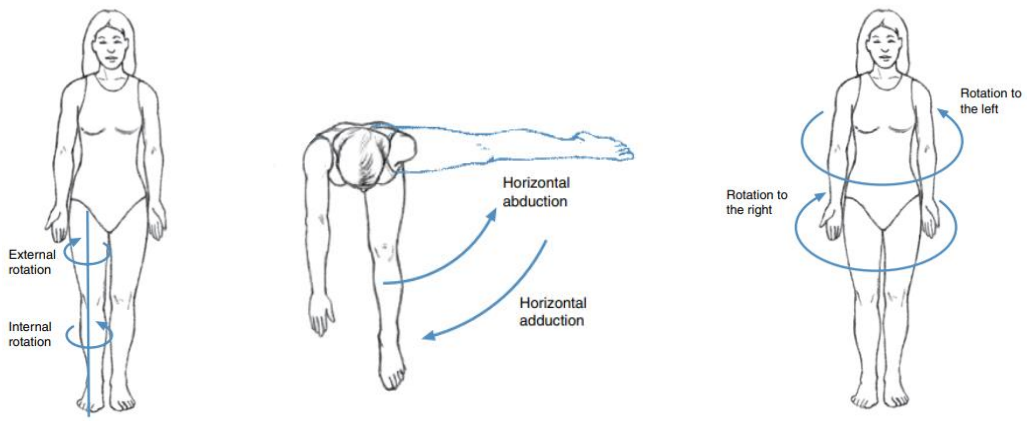

Figure 1.6: *Representation of lower extremities movements in the transverse plane.*

1.4.5 Complex Movement of Ankles

The ankle is a complex joint, most of its movements are a combination of rotation around complex axes. Considering the ankle movements in the three different planes of space, the combination between eversion, dorsiflexion and abduction is called ***"pronation"*** while the combination between inversion, plantarflexion and adduction is usually known as ***"supination"*** *(Figure 1.7)*. Pronation is necessary to the body for absorbing the impact shock with the ground, during the first contact at the moment the heel touches the ground, while supination increases the efficiency at the propulsion instant [5].

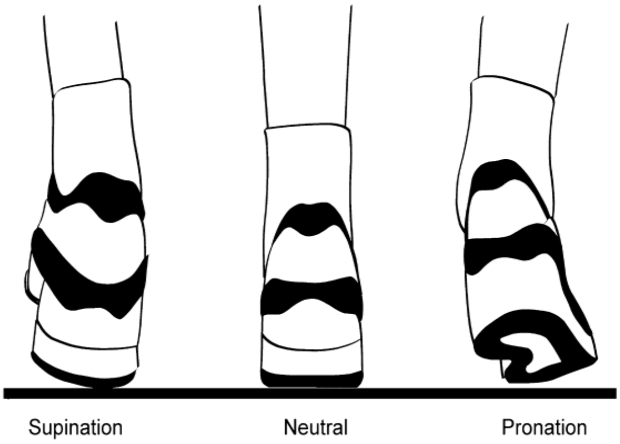

Figure 1.7: *Representation of the complex movements for ankle.*

1.5 Lower Extremities Anatomical Tips of Rotation

1.5.1 Ankle Joint

Anatomically, what is generally known as an "ankle joint" may be more correctly called ***"ankle joint complex"*** *(Figure 1.8)*. In fact, it is the combination of the talocrural (or ankle, articulation between talus and tibia) and the subtalar (or talocalcaneal, articulation between talus and calcaneus) joints. However, using external anatomical landmarks for studying joints, as happens in most of biomechanics surveys, makes it impossible to distinguish the two joints. Today, the ankle joint could be also called ***"tibia-fibular articulation"*** [32].

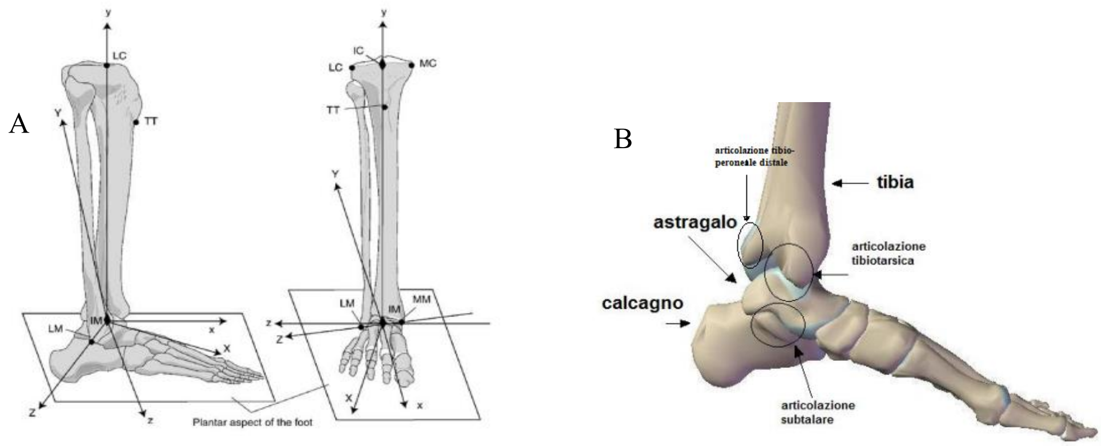

Figure 1.8: *Representation of talocrural and subtalar ankle joint from a physical point of view (A) and from anatomy point of view (B).*

In addition to the main anatomical planes already described, for the ankle, it is important to consider also the ***"torsional plane".*** This plane contains the point IC (inter-condylar) located in the midway between the tips of the lateral tibial condyle (LC) and medial tibial condyle (MC), MM (tip of medial malleolus) and LM (tip of lateral malleolus) *(Figure 1.9)*. The different orientation of origin of the separate joints requires two different coordinate systems [32]:

- The tibial-fibula coordinate system: with origin in IM (inter-malleolar point situated midway between medial malleolus (MM) and lateral malleolus (LM)), the "Z" axis as the line connecting MM and LM, the "X" axis as line perpendicular to the torsional plane and anteriorly, and the "Y" axis as the one perpendicular to the other two.

- The calcaneus coordinate system: origin in common with the previous system, the "x" axis perpendicular to the frontal plane, the "y" axis the same of the tibial-fibula axis and the "z" axis perpendicular to the other two.

According to both different motion systems, the motion of the complex ankle joint is a combination of them *(Figure 1.9)*:

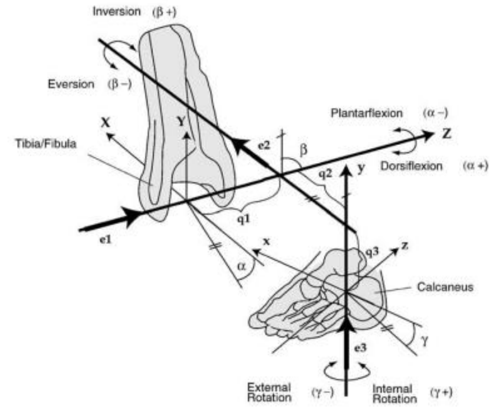

Figure 1.9: *Representation of ankle joint complex.*

A rotation (α) around the "Z" axis of the tibial-fabula (thought medial and lateral malleolus) system represents the dorsiflexion or plantarflexion; a rotation (γ) around the "y" axis of the calcaneus coordinate system (through tibial-fabula axis) fixed on the calcaneus determines the internal or external rotation; the rotation (*β*) on the axis perpendicular to the other two identifies inversion and eversion [32].

1.5.2 Knee Joint

Two segments compose this joint: the thigh (femoral segment) and shank (tibial segment) segments. Also in this case, in order to describe the motion of the knee, it is necessary to use two different coordinate systems, each associated with one segment: the ***"Tibial Cartesian coordinate system"*** and the ***"Femoral Cartesian coordinate system"*** *(Figure 1.10)* [7].

- TCS has the "Z" axis as the mechanical axis for the tibia, it is the fixed axis and vertical, therefore useful to quantify the internal-external rotation of the tibia; the "y" axis a midway line between the two intercondylar eminences and the "x" axis, usually oriented laterally or medially in the knee.
- FCS, at the same way, has the "Z" axis as mechanical axis, it connects the head of femur (the great trochanter according with literature) to a midway point between the medial and lateral femoral condyle; the "X" axis is considered the femoral-fixed axis, is perpendicular to "Z" and it passes through the medial and lateral femoral epicondyles; finally, the "Y" axis is perpendicular to the other two and oriented anteriorly [35,36].

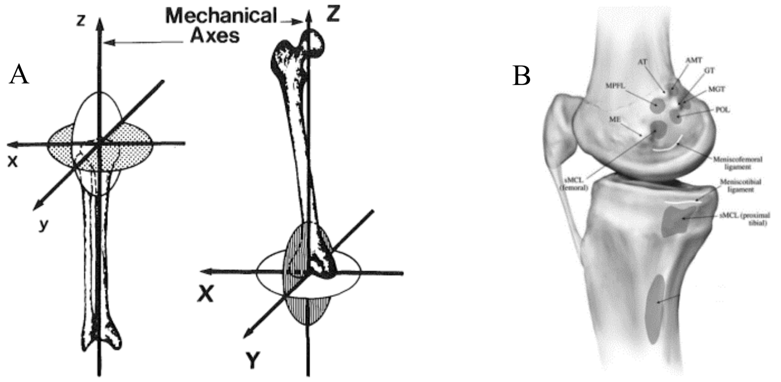

Figure 1.10: *Representation of tibial and femoral knee joint from a physical point of view (A) and from anatomy point of view (B).*

According to the JCS, the complex knee joint is described by the combination of both segment systems:

The “z” or tibial fixed axis describes the internal and external rotation, obtained by analysing the floating angle of the rotation of axis, while the “X” or femoral-fixed axis is the reference parameter for flexion and extension of knee joint, quantified by analysing the rotation of the floating axis with respect to its anatomical position. Finally, the floating axis, perpendicular to “z” and “X”, is important to define the adduction and abduction of the knee complex joint *(Figure 1.11)* [7,37].

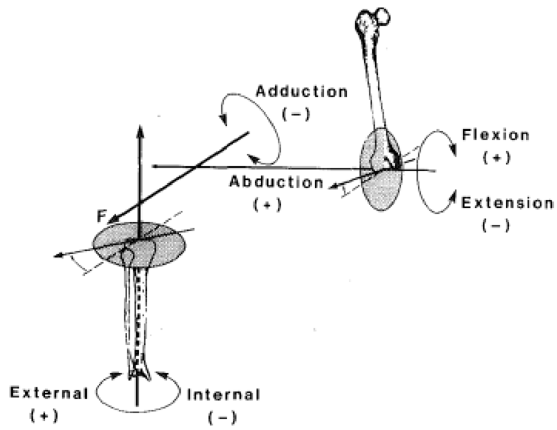

Figure 1.11: *Representation of ankle joint complex from a physical point of view.*

1.5.3 Hip Joint

The hip joint has been described uniquely in literature, but always as the combination of two cartesian systems. Most of times, it is not possible to consider the hip joint accurately because most of the anatomical landmarks are not accessible in vivo, but just in radiographic analysis. It is necessary a conventional system that may be adopted in all measurement *(Figure 1.12)*.

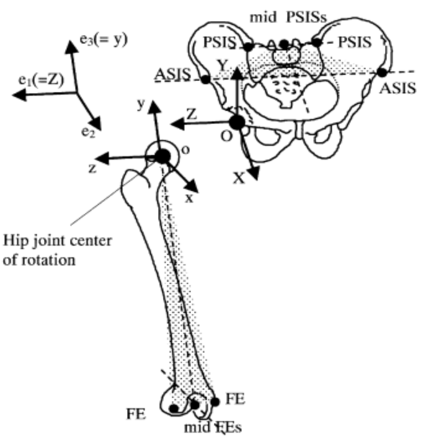

Figure 1.12: *Representation of pelvic and femoral hip joint from a physical point of view.*

As mentioned, two different coordinate systems for describing rotation motions parallel axis are used . One is the ***“pelvic coordinate system”***; with origin in the centre of the hip rotation, the “Z” axis: a segment that connects the right and left ASISs points (the anterior superior iliac spine), the “X” axis going from the midpoint of the right and left PSIS segments (posterior superior iliac spine) and orthogonal to the Z axis, while the “Y” axis is perpendicular to the others. The second system is known as the ***“Femoral coordinate system”***, with origin exactly in the same point of the other system, the hip centre of rotation [6].

According to the complexity of the hip, defining the centre of rotation is challenging, so according to the adopted convention, the ***"grand trochanter"*** can represent a valid alternative when corrected by a coefficient for biomechanics analysis systems in order to account for the error [38]. The correcting factor is important especially for the hip joint, where a small error in the reference point becomes bigger during analysis. In any case, the "y" axis is a line connecting the grand trochanter to the midpoint of a segment connecting both FE (femoral epicondyle). The "z" axis is perpendicular to the "y" axis and parallel to the segment connecting both the femoral epicondyle and the "x" axis: a line perpendicular to the others two axes.

According to the combination of both cartesian coordinate systems, the resultant interpretation is:

The rotation around the "Z" axis describes the hip flexion or extension, while around the "y" axis, also known as fix femoral axis, is the reference axis for the internal or external rotation. Adduction and abduction are evaluated by an axis perpendicular to "Z" and "y".

Chapter 2

Running Movement Pattern

In this chapter, the running gait will be described, in all its phases, including time variation series and characteristics parameters. In addition, it will be shown that variation showed by parameters during running motion is symptomatic of changes in the running movement pattern.

2.1 Biomechanics and Phase of the Running Cycle

A branch of the vast field of biomechanics is focused on studying different walking and running patterns; this specific niche is called ***"biomechanical running"***. The principal aim of this subject is to describe the function, the structure, the overall capability of the kinetic chain and lower extremities involved in running. Biomechanics running can also be used among other disciplines to diagnose and treat injuries.

The human gait *(Figure 2.1)* is a loop of alternating sequences in which the body is at first supported by one limb and then by the other one continuously. Normally, the ***"support phase"*** is identified when the foot is on the ground, the only one that generates propulsion thanks to a force transmitted to the ground by the runner. On the other hand, when both feet are in the air without any ground contact, the phase is called the ***"recovery phase"***. However, this convention is little used [33].

In running, the most frequent and sensible body movements happen in the sagittal plane; this is confirmed by the predominant magnitude of the force applied to the body's centre of mass in the horizontal and vertical direction of movement, compared to the medio-lateral direction of motion. It is the ground forces that are mainly responsible for motion. As they create moment in the joint, this results in a source of propulsion [9].

Although running, as walking, is a cyclic movement, every subject can show possible angle and structure differences between the two limbs, and no one shares the identical anatomy during motion. A running cycle is described by several phases: ***"stride"***, ***"step"***, ***"stance phase"***, ***"float phase"*** and ***"swing phase"***. Additionally, many parameters such as ***"step frequency"***, ***"step length"***, ***"stance time"***, ***"flight time"***, ***"stance vertical displacement"*** and ***"flight vertical stiffness"*** as well as two different instantaneous moments, ***"foot-strike"*** and ***"toe-off or take-off"*** are useful to characterize a specific pattern.

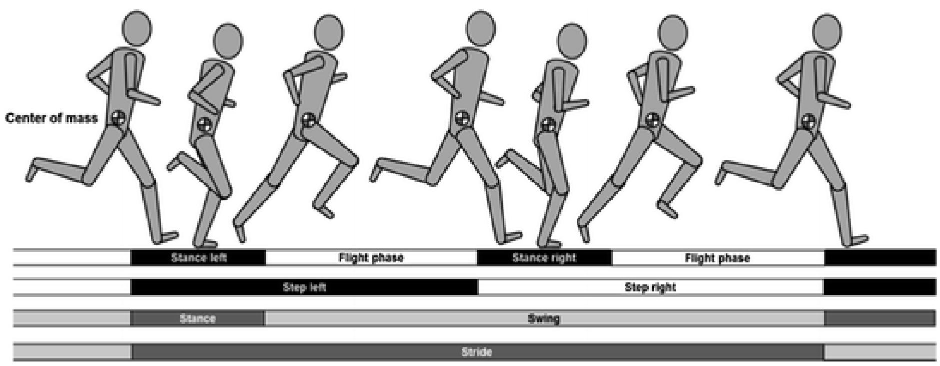

Figure 2.1: *Represents the different phases during a running cycle*

Generally, "foot-strike" is the time at which the heel touches the ground. The first contact with the ground can happen at different levels of the sole of the foot, determining ***"heel-strike"***, ***"midfoot-strike"*** and ***"fore-foot".*** During heel-strike, the heel touches the ground first, and in supination, while most of time it finishes in pronation; the foot at the ground contact strikes for 70% with the heel use this way as first contact with ground. The midfoot strike represents a more instable impact, that according with shoes worn from the runner can evolve into a heel or fore contact respectively. Only 30% and 0% of runner use the midfoot and forefoot strikers [10]. The vertical component of the impact foot-strike may be essential for stability and robustness in the swing phase of running [39].

The "toe-off or take-off" is the time at which the heel rises from the ground. For example, a fore-foot runner tends to finish the stance on lateral fore-foot in supination.

In order to fully describe a running gait, is also necessary to define a:

- ***STEP***

  Two steps are usually combined in a stride. This means two occurrences of foot-strike and four take-offs. It is defined as the time from foot-strike of one foot to the foot-strike of the other foot. Normally, a step is characterised using ***"step frequency (SF)"*** and ***"step length (SL)"*** both parameters are influenced by different running styles. However, by changing the step frequency, also the vertical oscillation of BCoM (Below Centre of Mass) changes (from 6 to 10 cm), but it should be minimized in order to avoid unnecessary work against gravity, increasing the energy cost [8].

  - STEP FREQUENCY AND STEP LENGTH

    Easier to measure, step frequency is a simple conversion of step time calculated as the ratio between 60 and step time, which is the sum of "stance time" and "float time". On the other hand, the product between SF and SL defines the running speed. For obtaining a better measure, it is therefore necessary to consider the ratio: SL/SF [40]; finally, after the previous considerations, the ratio SL/SF can be assumed as the proportion between the work done to move the limbs and accelerate the BCoM *(Figure 2.4)*. Numerous studies have shown that increasing the speed of running increases both the frequency and the length of steps. Under 20 km/h, the increasing SL is more pronounced with respect to SF due to great vertical forces, which have a greater impact with speeds higher than 20 *(Figure 2.2)*. At the same time, many studies discovered that a higher step frequency relates to an acute energy consumption. This makes it necessary to find a compromise spending less energy reducing SF and reusing the same energy for a longer step for example [9].

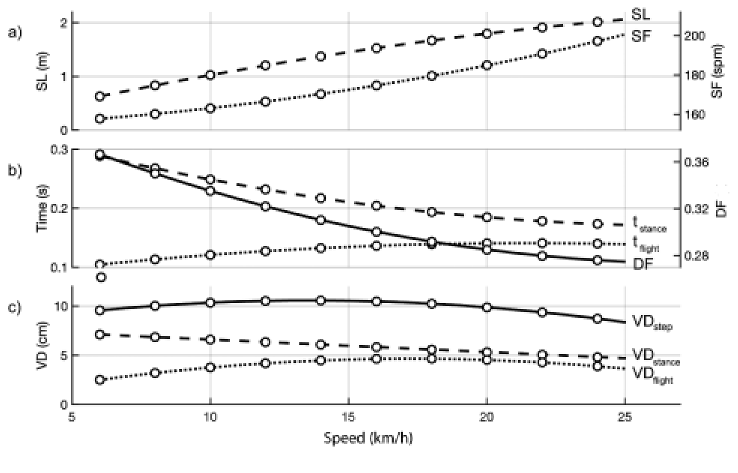

Figure 2.2*: Represents how increasing speed changes: step frequency and step length (a), stance time and flight time (b) and vertical stance displacement and vertical flight displacement (c).*

- ***STANCE PHASE:***

This phase begins with a foot-strike, continuing with midstance, and ending with the toe-off. During the foot-strike, muscles, bones and joints of foot and lower extremity together absorb the impact energy of the foot on the ground. Immediately after the impact with the ground, the multiplanar subtalar joint acts on the ankle causing pronation of the foot that close to the stretched plantar fascia expands the foot and absorbs the landing [5]. These complex movements are accompanied by a dorsiflexion of the talocrural ankle, slight flexion of the knee and hip extension until it is roughly over the ankle. A progression of the stance phase to midstance promotes a change of foot position from pronation to supination and a flexion of the ankle in preparation of take-off, with continues knee and hip extension. The stance phase is usually described using ***"stance time"*** and ***"stance vertical displacement"*** [9].

- STANCE TIME

It is the time that describes how long the foot touches the ground during a stance phase. Increasing the running speed, the stance time decreases. In order to keep the speed constant, however, it is necessary to increase the amplitude of the ground reaction force and to always develop the same impulsion. This is a force developed during running when the foot touches the ground and the ground reacts with opposite force used as propulsion system. According with what was previously told, stance time is the only factor directly connected to running economy cost and maximal running speed. In fact, an increase of t_{stance} reduces the energy running cost and increase the maximal running speed.

- STANCE VERTICAL DISPLACEMENT

It represents two thirds of the step displacement. One of the most important mechanisms used to explain the VD_{stance} is the inverted pendulum *(Figure 2.3)*. This model, thought of as a rigid pole with a ball on the top (representing the BCoM), predicts that the maximum of the centre of mass of the body is at the midstance. This is true for a walk because during running, it is necessary to consider spring properties to the rigid model. Halfway of the stance phase, the body centre of mass reaches the lowest point while the highest one is achieved only during the flying phase. The combination of the two models (spring and inverted pendulum) is a fidelity representation of reality [8,9].

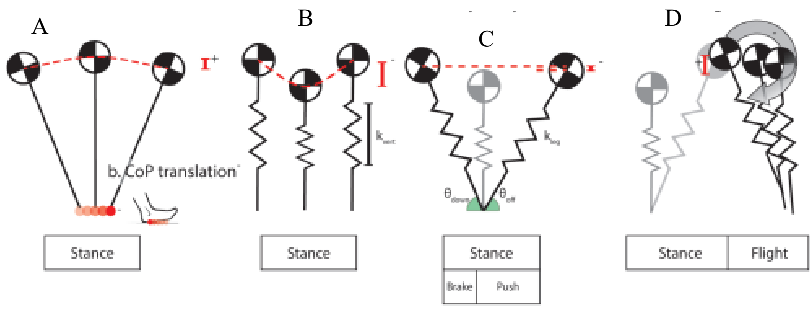

Figure 2.3: *Representation of the vertical displacement of the body centre of mass considering the inverse pendulum (A), the possible spring on rigid system (B) the influence of the strike angle on spring (C) and the spring behaviour during flight and stance phase (D).*

Considering our legs as a pendulum, as previously described, it makes the model dependent on the exchanged energy at each oscillation caused by the ground impact. During a running gait cycle, a constant amount of energy is changed and the energy it took back from the body-system during the take-off and swing phase is dissipated during ground contact. Just a fraction of the energy dissipated is returned; the lost power quantifies the energy running cost [41].

- ***SWING PHASE***

  This phase occurs when the lower extremity swings through the air from a take-off to the next foot-strike. At the toe-off rectus femoris and anterior tibialis muscles are the most active, while hip extensors and hamstrings are more stressed during late swing phase. During the swing phase, the hip continues to extend until the maximum flexion of the knee, before starting flexing and extending again until the moment before the foot-strike instant. After reaching the maximum flexion, the knee begins an extension phase that brings it in a state of being slightly flexed exactly at the moment of touchdown of the foot with the ground [5].

Stance and swing phase are only used for a single lower extremity each time; on the other hand, a focus on both lower extremities together identifies a new parameter: the "float phase".

- ***FLOAT PHASE***

  In this phase, both lower extremities are in air and there is no contact between feet and ground. During float time, the hip flexion causes a combination of forward rotation and twisting of the pelvis. Typically, two parameters are used to describe the float phase which is also called the flying phase: ***"Float or flying time"*** and ***"float vertical displacement (VD_{flight})"***.

  - FLOAT TIME

    It is the airborne time; a period in which both limbs do not touch the ground. The float time, also called flight time, depends on many factors; one is the age, an older runner tends to have a shorter float time, and, males have usually longer flight times than females. However, in all cases, by increasing the speed, the flying time increases. Typically, t_{flight} ranges between ~ 100 to 150 ms with a ballistic parabolic trajectory of BCoM. As a direct consequence of that, the distance covered from the centre of mass is proportional to the speed and angle at the take-off instant. The float phase is a good index of a runner's ability to generate power during the relatively short stance phase [9].

  - FLOAT VERTICAL DISPLACEMENT

    The vertical displacement during the flying phase reduces the amount of work necessary to bring legs forward. Normally, it is the result of the vertical force generated during the stance phase and therefore relates to VD_{stance}. One-third of a step displacement is associated with the vertical displacement during flying time *(Figure 2.4)* [42].

- ***STRIDE***

  This term is used to indicate one complete running cycle. Normally, it is considered from the take-off to the following toe-off of the same leg. According to the nomenclature, a stride is two steps in a row [8]. Most of the time, during study and measurement, parameters and phases are collected just for one step, neglecting the equally important stride. The cycle time (heel strike to heel strike of the same foot) for an endurance run is about 600 ms while it is less than 600 ms for sprint running [43].

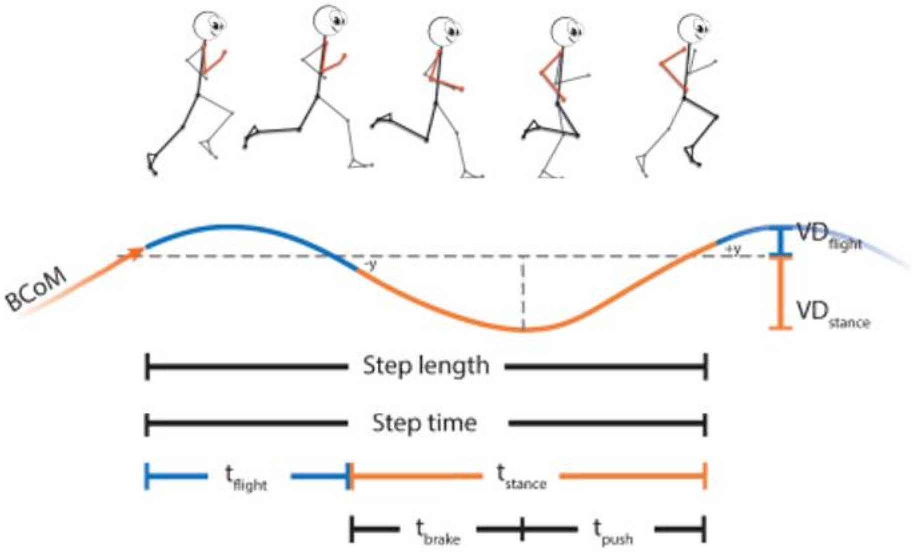

Figure 2.4: *Representation of displacement of BCoM (A) and times and phases (B) during a running pattern.*

In conclusion, a long stance time generates a large excursion of the inverted pendulum and a decrease of the GRF (ground rection force). Increasing the stance time, the flight time decreases and the vertical displacement becomes lower. On the other hand, a long stance time is really energy expensive to support for long distance running, so in order to keep the vertical displacement low, one needs to produce the necessary force in short stance time; this is possible increasing the stiffness of legs that are compressed like springs [44].

2.2 Kinematics of Running

The kinematics of running movement is a linear motion, in particularly of the centre of mass (the condensation of body for physics), the only point with just translation movement. All other points, especially joints, are rotation centres. Many parameters as angular displacement and velocity are used to describe the angular motion, but the most important are ***"joint angles"*** and ***"relative acceleration"***.

2.2.1 Angle-Time Diagram

It is a collection of time series data, a list of variations during time. It shows how is the variation trend of joint angle during time in a range of fixed strides. Although, it is a qualitative analysis, it can also be used thanks to gradients and curvatures (velocity and acceleration of movement) with a quantitative scope. Acceleration, for example, is used to identify the take-off and toe-off instants. Toe-off is defined as the local minimum of the shank angular acceleration in the sagittal plane, while the heel-strike is the time of foot local minimum angular acceleration in the sagittal plane [45]. The stance phase during running represents on average the 31% of the stride cycle [43] *(Figure 2.5)*. As previously described, considering a step, the time of swing and stance phase changes with speed, namely stance time decreases and flying time increases with rising speed. Between 10 km/h and 18 km/h the stance time varies from 289 ms to 194 ms while the aerial time normally, between 69 ms and 111 ms [43].

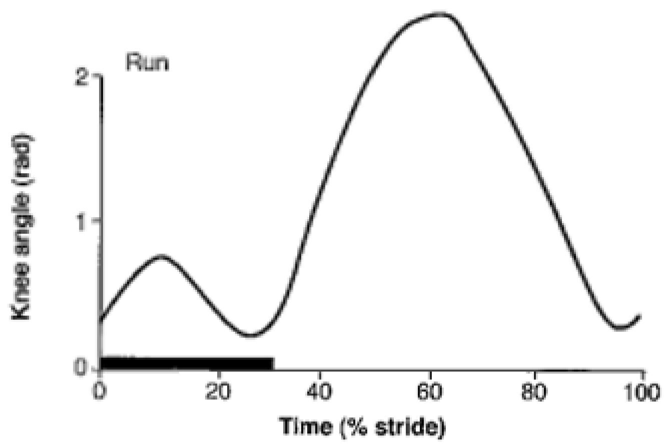

Figure 2.5: *Representation of knee angle in flexion or extension during a stride of running. 0 rad indicates a complete extension and the black horizontal bar the stance phase.*

At the same time, it's possible to observe that; in an angle-time diagram representing the flexion and extension movement, the knee is slightly flexed until to 10% of stride after the foot-strike (left) before almost reaching the end of stance phase, the maximum flexion at the 60-65% of stride and again the almost full extension at the toe-off (right). The knee has two periods of flexion: one during the stance phase and the other in the swing phase. The flexion detected at the beginning of stance phase, during foot-strike, is useful as shock adsorbing movement while the quadriceps work in eccentric to avoid excessive flexion, producing negative work. On the other hand, in the swing phase rectus femoris eccentrically contracts work, preventing the over-flexion of the knee, while the hamstrings eccentrically contract work preventing overextension during the late swing phase [5]. From the displacement of knee is possible to obtain the angular velocity that is considered positive in extension and negative during flexion.

Hip joint is flexed during the swing phase, while it is extended during the stance phase. The peak of hip extension is at the toe-off, at the late swing, when the foot is under the centre of gravity. Increasing speed, the extension of hip decrease and increases the speed with which the hip flexes.

Ultimately, every time that the foot touches the ground, it absorbs up to three times the weight of the body, acting as a shock adsorber, transferring the weight to all lower extremities. At the impact, the forefoot is abducted, the foot is everted; and the ankle is dorsiflexed, generating internal rotation of tibia. It's in the halfway of the stance phase that pronation reaches the maximum *(Figure 2.6)*.

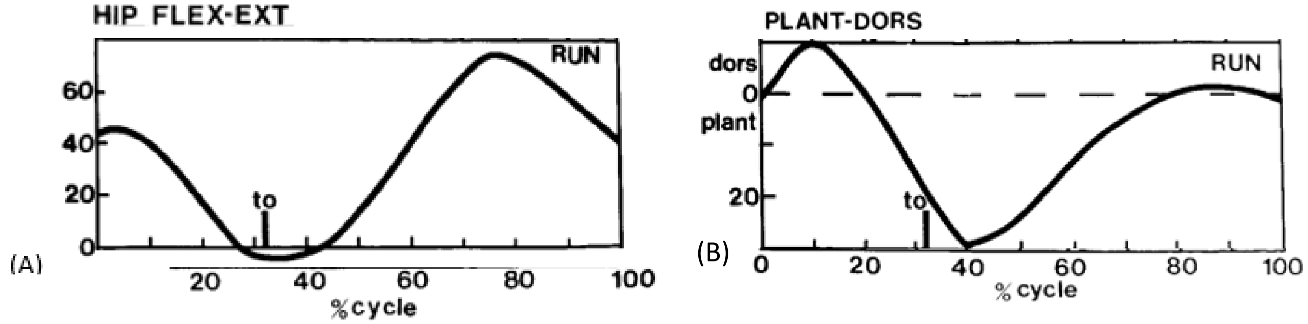

Figure 2.6: *Representation of hip flexion-extension (A) and Ankle plantar-dorsiflexion (B) as a function of the gait cycle.*

Joints movement and segments angle, in particular for lower extremities, are certainly more represented in the sagittal plane, than on the other planes. Nonetheless, the frontal plane also, returns important results, especially for the abduction or adduction of ankle. During running, it experiences very complex movements and not only inversion or eversion. Knee is considered just for valgus pathology, while *(Figure 2.7)* at the foot-strike the hip, as an absorber, helps to limit the impact, in particular if a little adducted for about 2°. In any case, at the toe-off the hip experienced an abduction of about 6° with a total range of motion limited to a variation of about 5° [46].

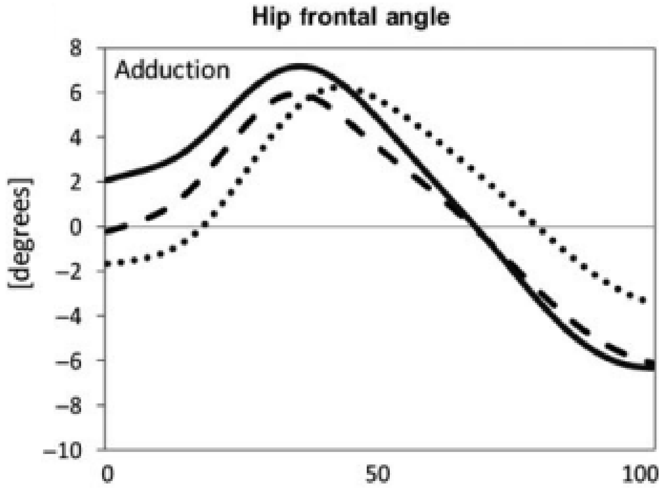

Figure 2.7: *Representation of adduction and abduction oh hip as a function of the difference stance percentage considered in case of young (continued line) and old (dotted line) people.*

2.2.2 Angle-Angle Diagram

Every movement of body involved a larger number of freedom degrees. Using angle-time diagrams could be really difficult represents the coordination and relative movement for many different joint angles, so Angle-angle diagrams reduce the number of variables, plotting angles against each other. The analysis of coordination during a motion represents a way to limit the freedom degrees.

If Angle-angle diagrams are compared to time-series graph, they represent a more quantitative analysis, correlating angles between different joints. Even if a movement is cyclic, the diagram usually represents only one cycle, which corresponds to one stride of running or to the average of multiple strides.

For example considering that all angle are average value because they change from person to person and from activity to activity, at the heel-strike the hip joint is usually flexed between 25° and 30° remaining almost unchanged during first moments after impact. The hip angle remains the same for the next 65 ms, more or less, the time of impact that generates the ground rection force. After, it begins to extend reaching an angle of about 21° at the toe-off moment, coinciding with the maximum knee extension, before decreasing at 10° during the swing phase [5,47]. At the swing phase, the thigh motion reverses direction almost immediately, and the hip flexes at a slower average rate than the simultaneous knee flexion, but the thigh continues to flex also after maximum knee flexion. At faster running speed, a greater propulsive force is generated and the hip extension at the take-off can increase by a further 5° *(Figure 2.8 A)* [10].

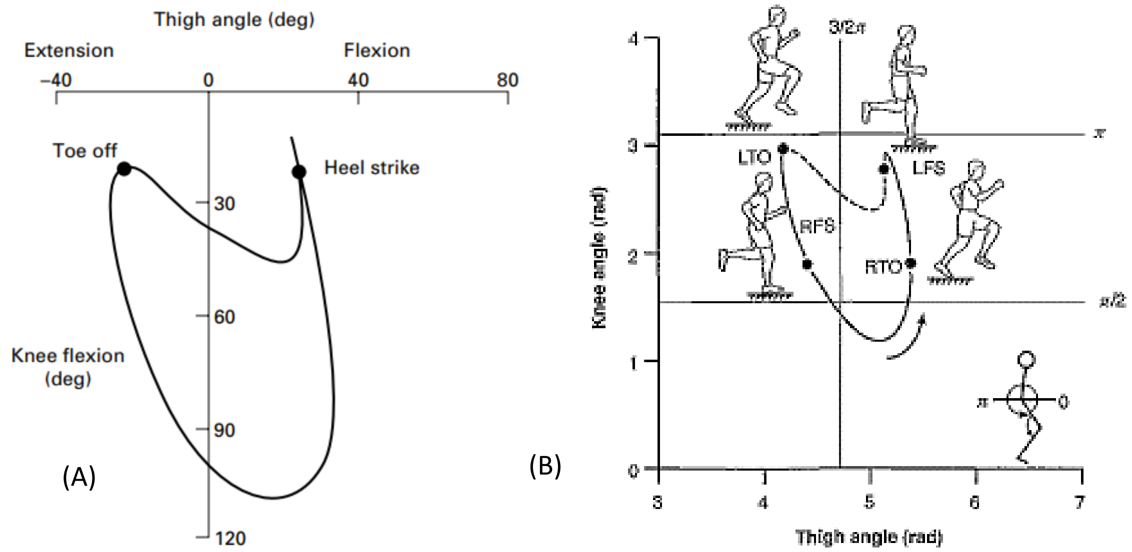

Figure 2.8: *Representation of knee flexion and extension as a function of thigh or hip angle for a complete stride of running at 3.8 m/s (hip angle is on vertical) (A), and hip-knee diagram during running at 4.2 m/s (LFS = left foot-strike, LTO = left toe-off, RFS = right foot-strike, RTO = right toe-off) (B).*

At the foot-strike instant the knee joint is slightly flexed to an angle of about 10°, before increasing the value of flexion between 20° and 25° in the early support period and continuing to approximately 45° at the midstance. In the latter support phase, the knee doesn't experience the fully extension remaining from 15° to 20° of flexion at the take-off. It's in the swing phase that knee go to maximum flexion and the angle can change between 90° and 130° according to the speed *(Figure 2.8 B) (Figure 2.9)* [8,10].

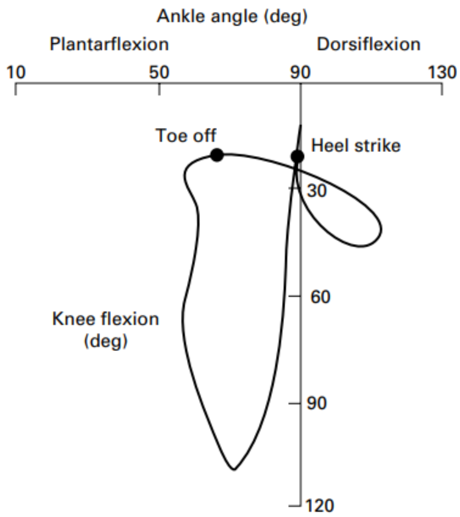

Figure 2.9: *Representation of knee flexion and extension as a function of ankle angle for a complete stride of running at 3.8 m/s (ankle angle is on vertical).*

At the heel-strike, the ankle joint touches the ground absorbing the impact in a plantarflexed position of 5°, that increases of other few degrees immediately after the foot-strike before experiencing, always in the first half of support phase, between 15° and 20° of dorsiflexion, approximately coincides with maximum knee flexion [11]. In the later part of support phase, an extension of knee brings the ankle plantarflexion up to 30° before the toe-off. In the swing phase, the foot plantarflexes up to 20°.

Sometimes, a very slight overshoot could happen when a higher-than-normal dorsiflexion and plantarflexion at the foot-strike is verified.

Additionally, the extension and the area of the diagram adds information to movement patterns. The extension and shape represent the variation in amplitude in the range of motion, while the increase of the area indicates faster rotation of motion, typical of a faster speed movement. The variability is larger during swing phase compared to stance phase *(Figure 2.10)* [8].

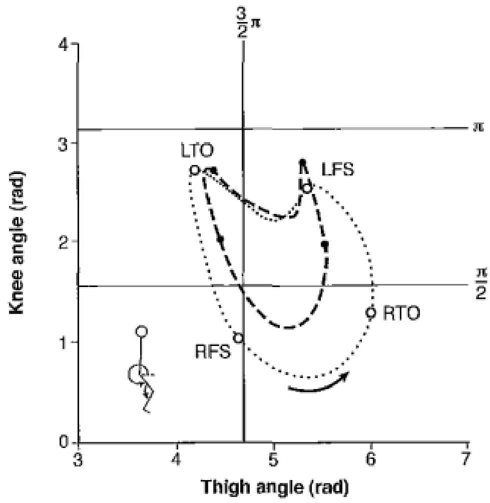

Figure 2.10: *Representation of angle-angle diagram of a runner who run at 3.89m/s (dashed line) and 7.6 m/s (dotted line).*

Comparing different joint angle movements and to analyse the "topological equivalence" between same joint patterns for example, represents the importance of these diagrams. Unfortunately, there are also disadvantages as it's difficult to understand where key events are, such as take-off and toe-off are, just by looking at the diagram. In addition, without considering "time-series", there is no relationship between shape patterns, slope = velocity and curvature = acceleration information is lost. Usually, nonlinear approaches like: ***"continuous relative phase"***, ***"Lyapunov exponent"*** and ***"Sample Entropy"*** (the last two described in chapter 3) are used as tools to analyse the human movement stability and coordination.

2.3 Kinetics of Running

During running, the movement of body is an important indicator of the load distribution during a foot-ground contact and the toe-off. The contact of foot with ground generates a reaction force from the ground to the foot. This force is distributed under the plantar surface and it is transmitted to the legs segments, accelerating them. This force is described by ***Ground reaction Force (GRF)"*** and ***"Plantar pressure distribution"***.

2.3.1 Ground Reaction Force

It is the force that the ground exerts on the performer [33]. It is divided in three different components: *"vertical component",* the most significative and opposes to the gravity force; *"anteroposterior component",* in the direction of motion responsible for acceleration or breaking, both under muscles control and half stance long each one. The entity of acceleration and breaking, such as ground impact, are speed dependent *(Figure 2.11 B)* [9]. Usually, the maximum breaking occurs approximately at the 22% of stance, while the maximum acceleration at about 70-76% of stance [48]. Usually, the GRF during propulsion impulse exceeds the braking impulse [9]. The last component is *"mediolateral* *component":* it is responsible for changes in direction. This type of force is unstable. In fact, it could be hard to understand when is medial or lateral, in particular during the first 35-40 ms of support.

- VERTICAL COMPONENT

It is divided into two main phases: *"impact"* (also called passive) and *"propulsive"* (or active) components. The impact occurs in the first 50 ms since the foot touch the ground [10], it is characterised by a rapid rise of ground force in little time. Midfoot strikers developed a smaller passive force during impact rising more or less directly to the thrust peak at the 35-50% of the total stance time. On the other hand, the active component controls the displacement of BCoM of body. It rises and decays slower, with a larger and higher peak in a range of time between 50 and 250 ms since the ground contact for medium runners [8,10]. As running velocity increases, the impact peak and rate of loading by GRF increases. In addition, the vertical component of ground reaction force was used to define the foot-strike and the toe-off moment, the main value for calculating the duration of stance and swing phase; a vertical GRF bigger than 20N identify the foot-strike, while the toe-off was identify when vertical GRF dropped below 20N [45] *(Figure 2.11 A)*.

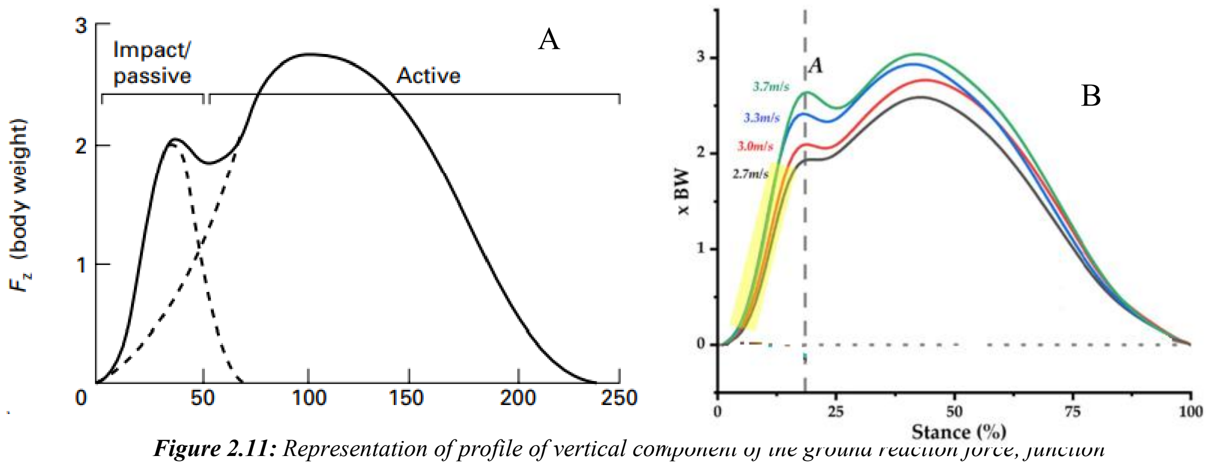

Figure 2.11: *Representation of profile of vertical component of the ground reaction force, function of time (A) and function of speed (B).*

Using a forefoot strike, the external impact decreases while the internal force transmission between joint and segment increases, especially for the ankle but also the entire body. Acceleration happens at the toe-off lower limbs and contributes for a 16-18% each one and the upper body for about 5% [4] In addition, the external force is higher than the internal one most of the time.

2.3.2 Plantar Pressure Distribution

It is important to analyse timing and ground reaction force distribution on the plantar of foot. 15 ms later after the ground foot strikes, pressure increases. Until the next 60 ms, the value of pressure in the heel is overcome by the pressure in the metatarsal heads. Only after 120-140 ms the forefoot reaches the peak of pressure during stance, almost in time with the take-off. In general, during the last phase of propulsion, the force is mostly given by the metatarsal (21%) and hallux (17%). A lower contribution is given by other toes (7-11% all together) [10] *(Figure 2.12)*.

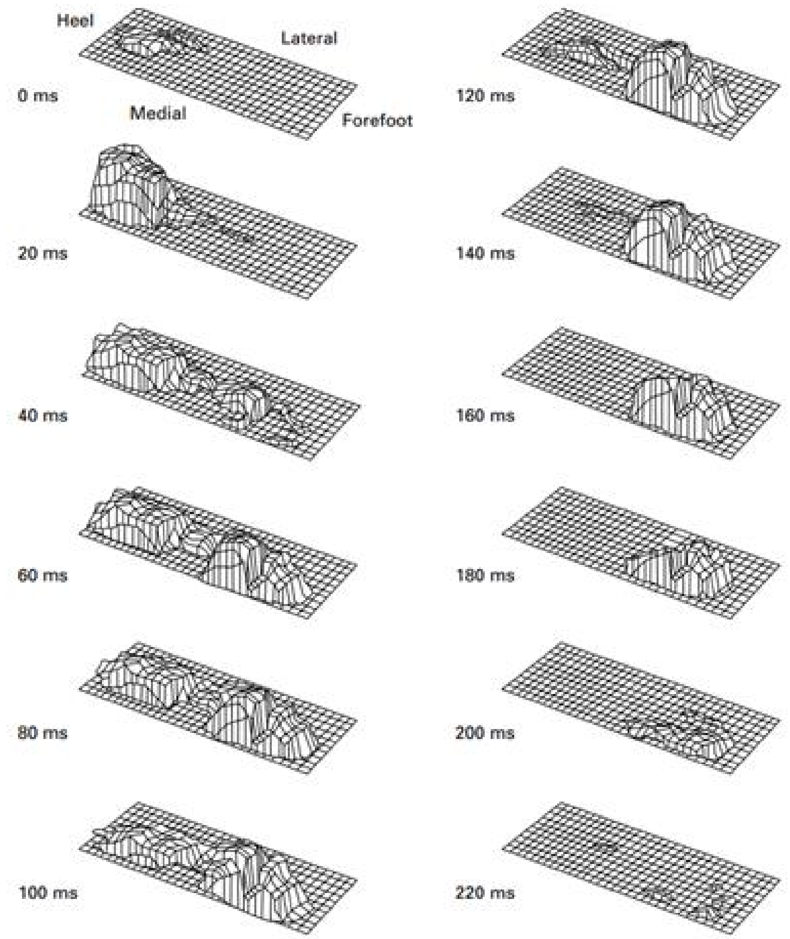

Figure 2.12: *Representation of plantar distribution pressure map during a stance phase of running at a speed of 4 m/s.*

Chapter 3

Dynamics Systems in Movement

In this chapter we'll analyse possible systems that can be used to describe the stability of a running movement patterns. In particular, "Non-linear Tools" will be considered.

3.1 Characterization of Dynamics System

A system is known as dynamic if it evolves in time with a specific pattern [49]. One of the most significant aspects of human movement is variability. It can be described as a normal change during multiple repetitions of a cycling movement, including the possibility of different patterns according to variable running performances. Variability is an intrinsic feature in all biological systems; no one can repeat the same movement in the same way twice.
Different theories such as Generalized Motor Program Theory (GMPT) or Uncontrolled Manifold (UCM) may be used to describe variability, but it's the Dynamical System Theory (DST) that is used in the current work. The first one considers the variation of movement patterns just as a simple result of error, while the second one associates the movement variability as a redundancy. [50].
DST provides important tools to describe phenomena. According to this vision, when a control parameter is changed above a critical threshold, the variability of the system increases, whilst its stability decreases. A transition from an unstable system state to a more stable state takes then place, typically referred to as bifurcation. Temporal variations in biological signals seem to be random noise but they exhibit ***"Deterministic patterns"***, defined as *"Chaotic"* [20].

The differences between random and deterministic systems are that a random pattern can be represented as a succession of variables unpredictable by the evolution equation which evolves over time, with trajectories in the state space not showing any recognizable pattern, while deterministic systems present randomness in the determination of following states of a system. In a deterministic system, by knowing the initial state of a system, it is possible to predict future states. In the same direction, a system is called "*Chaotic"* if it presents non-linear elements and properties, small perturbations on the initial conditions can produce large changes in the future states of the system, and trajectories in the state space show a recognizable pattern, despite not perfectly repeatable. but with clear trajectories that are not overlapped [22]. Finally, a periodic time series provide perfectly overlapping trajectories.

Dynamical System Theory, as implication for sport biomechanical, usually conceptualise the human movement system as ***"non-linear dynamical system"***, a system in which *"the principle of additive of effects"* is not true. These systems have many independent degrees of freedom and they are free to vary in space and time. They are usually called *"open"* and operate far from the equilibrium state. These systems propose the most stable solution during running gait provided by the interaction between ***"self-organization"*** and ***"constraints"*** [22]. Tools that have been used to study non-linear system include *"Approximate Entropy"*, *"Sample Entropy"*, *"Correlation dimension"*, *"Largest Lyapunov Exponent"* and *"Detrended Fluctuation Analysis"* [21].

Self-organization is an emergent property of generic processes for functional coordinative states, or attractor states in dynamical parlance while, constrains are usually defined as *"internal and external boundaries,* *limitation or design features that restrict the number of possible configurations that complex systems can adopt"[20].* They are divided in three main categories and identify the source rather than the real nature of them:

- ***Environmental constraints:*** they are external to the movement system. Examples of this kind of constrain are light, temperature and altitude, while for running could be considered the reaction forces exerted by the ground or other contact surfaces and shoes. Different running surfaces are one of the most important environmental constraints, but at the same time is possible to notice that are more challenging to manipulate during experimentation.

- ***Organismic constraints:*** they are internal to the individual movement system. Usually, they are divided in two different families: *structural constraint* and *functional constraints*. The first one more physical and constant over time *(stature, anthropometric and inertial characteristic of body, the number of mechanical degrees of freedom and ranges of motion of articulating* structures), while functional constraints are more physiological or psychological *(intention, emotions, memory, decision, intelligence and perception).*

- ***Task constraints:*** they are not physical constraints, are requirement or constraints that are necessary for a successful performance (the law of the game). Task constraints are usually specific for any kind of performance.

As previously described, a dynamical system is deeply dependent from initial conditions and constraints that characterize the system from the beginning. However, also perturbations influence the stability of a dynamic system. Thus, [51] the local dynamic stability is defined as the sensitivity of a system to "small" perturbations as natural stride-to-stride variation during gait locomotion. A system with large variability doesn't necessarily exhibit poor stability, as there is no correlation between variability and stability, variability doesn't necessary predict instability. However, while variability is quantified from linear statistic tools, local stability is usually defined using nonlinear dynamics tools. Despite of different tools, movements variability has experienced different interpretation and assumption such as *"that high level performers have an invariant movement or at least a large tendency to be invariant"*, *"that there is just a most efficient and effective way of performing during motion for the majority of the population"* or more *"that every variability is treated as an error from the invariant movement pattern"* during years [21].

A measurement is usually conducted to obtain an evolution of signals in time (Time series). ***"Time series"*** is just a list of numbers that are measured sequentially in time. Usually, it is a function of discrete values where the time intervals between two values is assumed to be constant. However, in order to examine a dynamic behaviour of a system from the time series is necessary to appropriately reconstruct the ***"State phase"*** where the behaviour of the system is embedded *(Figure 3.1)*. The ***"State phase"*** is a state vector where movement of a system in the space can be exactly described [52].

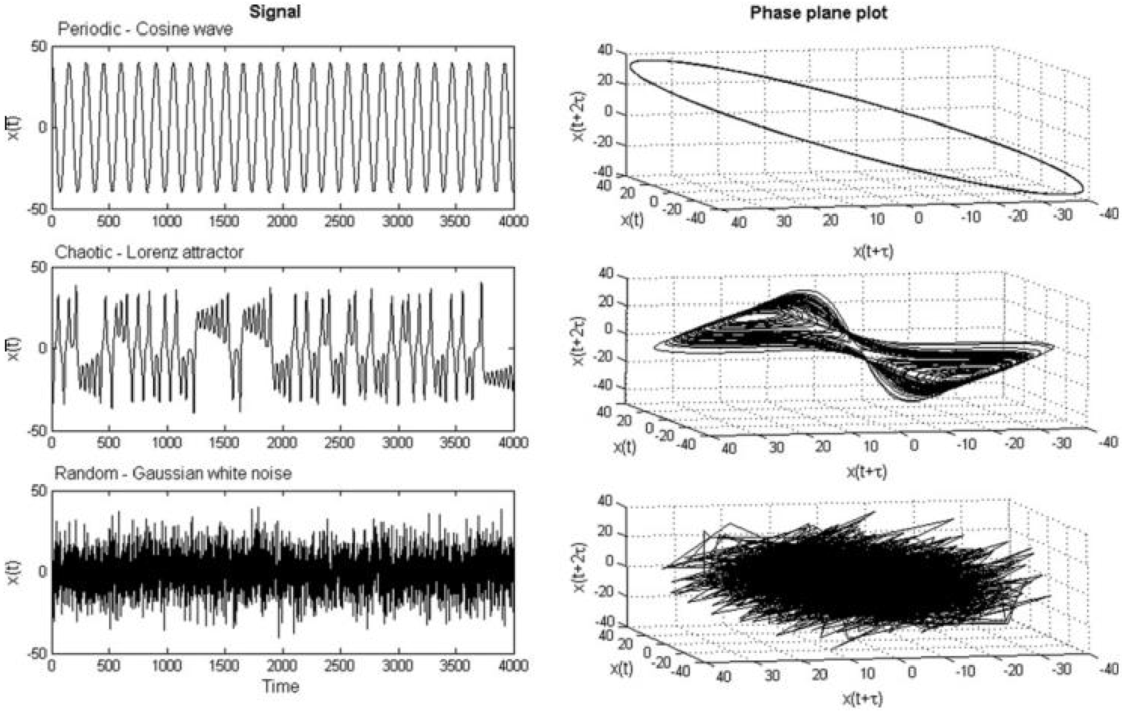

Figure 3.1: Representation of a periodic, chaotic and random signal as time series (on the left) and in the state phase (on the right).

The adaptability of a system under control with an optimal movement variability can classify a chaotic temporal variation with the concept of "predictability". A chaotic temporal variation in a steady state, under environmental stimuli and stresses, can move to a more or less predictable system. A decreasing in the state of variability reduces the complexity of the system rendering its more rigid and predictable. On the other hand, an increasing in the temporal variations renders the system noisier and more unpredictable even if, also in this case less complex too [21] *(Figure 3.2)*.

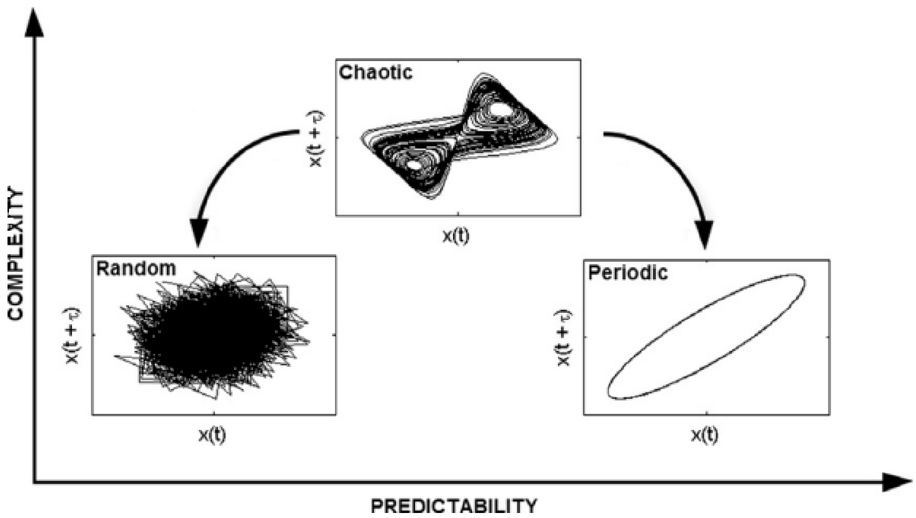

***Figure 3.2**: Representation of possible evolutions to a higher or lower complexity/predictability of a chaotic system after local perturbation*

3.2 Largest Lyapunov Exponent

It is a measure of the rate at which two near trajectories, in the state space, diverge, i.e., the exponential separation of two trajectories in the state space. Larger is the divergency rate of two neighbour points, the higher is the instability of the system, which is largely affected by initial conditions.
Most of time Lyapunov exponents are seen just as a mathematical tool, reason why *"LyE is calculated as the slope of the average logarithmic divergency of the neighbouring trajectories in the state space"[23]*.
Considering a *"periodic time series"* previously shown, there are no difference between trajectories, every loop is perfectly overlap from the others, so as a consequence of no divergency, the LyE is null.
A different behaviour is experienced for a *"Chaotic and random time series",* in which the Lyapunov exponent are not zero. It is clear that higher is the instability of a system, larger it's the value of LyE.
Therefore, LyE is a possible tool to estimate the local stability of a system [23].
Usually, the number of point necessary in input for the computation of Lyapunov exponent is between 1000 and 10000, even if larger data sets can be used. From studying, it has been found that the value of Lyapunov exponent is stable and unvaried after 35 repeating gait cycles, that corresponding to about 7000 data points, with a sampling frequency of 180 Hz [45,51,53].

First of all, an appropriate state space is defined using original data and time-delayed copies from the time series *(Figure 3.3)*. Then, a state vector is created in the state space defining geometric structures of the dynamical system (1), by calculating the ***"d"*** and ***"T"*** parameters of the state space. The variable *"d"* is embedded in the system and it represents the number of delayed copies of the signal which are necessary to reconstruct the dynamics of the signal in the phase space (i.e., the dimension of such space), while the variable ***"T"*** is the *"Time delay"* between two consequence points and an integer value (TΔt) of how many points describe time series [52].

$$X_i = [x(t_i), x(t_i + T\Delta t), x(t_i + 2T\Delta t), \ldots, x(t_i + (d_e - 1)dT\Delta t)] \quad (1)$$

The right time-delay is evaluated from the *first minimum of the Average Mutual Information* (AMI) function [39] while the variable *"d"*, also called ***"embedding dimension"***, is determined with the *"global false nearest neighbours"* algorithm [53] and, it represents, as previously mentioned, the minimum number of dimensions necessary to develop the dynamical system structure. The value of "T" and "d" shouldn't be too large or too small because, points with too large distance are considered independent and essentially random, while points too close together are not completely independent. However, two objects should be close enough but with sufficiently independent and, smallest as possible such that the global nearest neighbour drops to zero. Usually, in lower extremities the dimension of the embedding variable "d" is about 5 during locomotion [54].

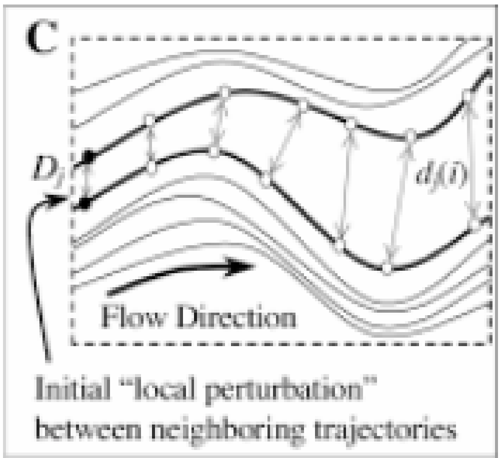

Figure 3.3: *Representation of a local region of state space, showing divergence of neighbouring trajectories resulting from local perturbations to the system;*

After that, the embedding dimensions were done from Global False Nearest Neighbours (GFNN) analysis, that compares the distance between neighbour trajectories at different and higher dimensions. Displacements between neighbouring trajectories is caused by local perturbations. The average rate of divergence in any point of them is calculated by the Lyapunov Exponent, providing a direct measure of local dynamic stability.
The largest Lyapunov exponent (λ) is defined using (2) [24]:

$$d(t) = De^{t*\lambda} \tag{2}$$

Where *d(t)* is the mean distance between the compared neighbouring trajectories, *D* the initial local perturbation and average separation between the trajectory and, *t* is the instant time considered. The Lyapunov exponent *(λ)* should be correctly evaluated between the two extreme limits *(D —> 0)* and *(t —> ∞)* but, time series, that are mostly considered, have finite length (same number of strides and reference points), so limits and LyE are calculated with specific published algorithms. In this study, it has been used the ***"Rosenstein Algorithm"*** [25].
Defining the limits of maximum finite-time, the number of points and taking the natural log from each side, it's possible to obtain (3):

$$Ln[d_j(i)] \approx \lambda*(i\Delta t) + ln[D_j] \tag{3}$$

It represents the mean distance between the *jth* pair of neighbours after *i* discrete timesteps [24].
From the last equation, it's possible to evaluate λ as the slopes *(Figure 3.4)* of linear fits to curve (4), that in this particular study is calculated within the first 0.5 gait cycles.

$$Y(i) = \frac{1}{\Delta t} \langle ln[d_j(i)\rangle \tag{4}$$

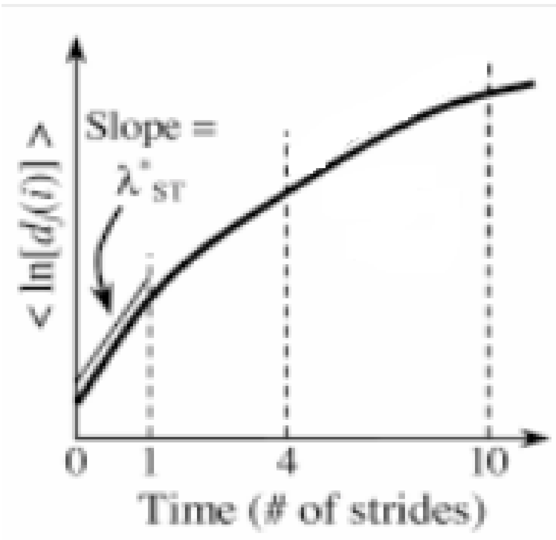

Figure 3.4: *Representation of the average logarithmic divergence of neighbouring trajectories, indicating the calculation of e Lyapunov exponents as the slopes of these curves in the ranges between 0 and 1 stride.*

If λ<0, two neighbour trajectories tend to converge while a λ>0 establish a divergence between two trajectories and the attractor is defined as chaotic. The numerical value is the entity of expansion or collapsing [49].
The advantage to use the *"Local Lyapunov exponent",* how it has been done in this study, is that there are more forward exponent and negative backward Lyapunov exponent that can be directly compared, rather than

just between *"Global Lyapunov exponent"* that represents how sensitive the dynamics is on the average over the attractor [55].

3.3 Sample Entropy

Randomness and its level are defined just in a mathematical way, through probabilistic tools and analysing statistical values such as mean, variance, asymmetry and kurtosis [23,49].

Entropy, whether it is: ***"Approximate entropy (ApEn)"*** or ***"Sample entropy (SampEn)",*** is a mathematical and useful specific method to characterize complexity, randomness and, to quantify the predictability and regularity of a time series data.

Entropy is a statistical concept; it is described with a uniformity test as a measure of uncertainty or variability (the more uniform the distribution, the higher the uncertainty and the higher the entropy). In addition, a more predictable and regular time series is less complex than an unpredictable one [51]. It can be used to describe every type of system, without previous knowledge about the source that generate the dates, simply knowing the data distribution.

Approximate Entropy measures the logarithmic probability that points of a time series at a certain distance will experience the same relative characteristic at the next same increment value within the state space. If the probability of distance is closed in the next increment comparison, lower will be the ApEn and the regularity of the system will be higher, while large differences in relative data points will result in higher value of Approximate Entropy, an index of higher randomness [26].

Actually, ApEn and SampEn don't allow to directly distinguish if the observed evolution during movement is given by deterministic or stochastic processes contribution [51], but conversely to the previously described non-linear tool, adapted for *"deterministic system"*, they reach a high statistical accuracy for both separate or mixed *"stochastic and deterministic system"*, the most frequent in biological state [56]. This is possible because the magnitude of noise is under the tolerance limit also with a small and finite data set.

However, the ApEn is not the best tool for two important implications:

- The consistency is depending on the "r" value, so it is not guaranteed that results may always comparable.
- Being influenced by the length of the data series (the number of measurement points influences the value of ApEn.

According with implications, the Approximate Entropy value, it suggests to show more regularity than the reality.

In order to solve the two approximate entropy biases is better to consider as main tool the ***"Sample Entropy"***, in fact it is based on similar principles, but able to solve the self-counting problem eliminating the ApEn bias. Similarly, ApEn, the sample entropy is reached from an algorithm [46] used to establish how much a series of data based on the existence of patterns is regular [28].
Sample Entropy is: *"the negative value of the logarithm of the conditional probability that two similar sequences of "m" points remain similar at the next point m+1, counting each vector over all the other vectors except on itself, that means a higher independency of the length of the series" [28].*

Typical values of SampEn are within 0 and 2 with a number of values approximately between [10^d, 30^d] and, *"d"* the dimension of the system [48]. Actually, it also works with few values and a big range between them but, always defining three different parameters: *"m"* (segment length), *"r"* (tolerance) and *"N"* (time series lenght) [23].

Sample entropy is calculated as follows [21]:

Firstly, the time series is divided in short vectors of length m. Then, for each of these vectors, one counts how many similar vectors of length m are present, within the tolerance t. The next step consists of taking the sum of all conditional probabilities and divide by N-m, gaining the term B_i. The same operation is repeated with vectors m+1 long, gaining the term A_i. From an operational point of view, SampEn is the negative logarithm of A_i/B_i.

$$\text{SampEn}(m, r) = \lim_{N\to\infty}\{-\log[A^m(r)/B^m(r)]\} \tag{7}$$

$$\downarrow$$

$$\text{SampEn}(m, r, N) = -\log[A^m(r)/B^m(r)] \tag{8}$$

$$\downarrow$$

$$SampEn(m, r, N) = -\log \frac{\sum_{i=1}^{N-m}\sum_{j=1, j\neq i}^{N-m}[\text{number of times that } d[|x_{m+1}(j) - x_{m+1}(i)|] < r]}{\sum_{i=1}^{N-m}\sum_{j=1, j\neq i}^{N-m}[\text{number of times that } d[|x_m(j) - x_m(i)|] < r]} \tag{9}$$

3.4 Others Tools

"Continuous relative Phase" along with *"Cross-correlations"*, *"Kohonen Self-Organizing neural networks"* and *"Vector coding"* [3] are classified as ***"Complex"*** analyses. They are widely used to measure and describe sets of time series data that coupling relationship between adjacent limb and joint segments. As consequence of application of self-organisation and constraints, they can be used to evaluate stability or variability among coordinative states. They are important alternatives to Lyapunov exponent and Sample Entropy.

Chapter 4

Trail-Running shoes Material and Technology

In this chapter it will be present an overview of how materials and new technologies can be adopted to produce normal and trail-running shoes with high performance. Different materials and technologies are more comfortable in some surfaces and not in others, they can influence the uphill and downhill movement pattern during a trail-running, or also by prevent people from experiencing injuries during a normal jogging session.

4.1 Minimalist and Barefoot Running Shoes

"Minimalist" is a general term for footwear that minimally interferes with natural foot movement due to high flexibility, low weight (< 170 g), heel-to-toe drop and stack height, and the absence of motion control and stability devices [12].

Their characteristics are: reduced cushioning, thin sole with a stack height of 10-15 mm and lighter weight compared to other traditional shoes, an improve foot strength and arch function. The ground impact of foot is focused on Mid/Forefoot [58].
Such a big group of footwear like this is divided in two different types *(Figure 4.1)*:

- *Barefoot running shoes:*
  They have no drop between heel and toe with a really minimal but flexible sole of 3-10 mm. Most of times there isn't any arch of support. They usually have more space on the front for toes with a wider toe box, similar to a "ducks' foot" or, separate toe pockets to let each toe flex individually. They offer the most similar feel to being barefoot.
- *Minimalist running shoes:*
  Their characteristics are in between barefoot and traditional shoes. Normally, they present a heel-to-toe drop of 4-8 mm with a normal toes box, a reduced cushioning but not arch of support too. The sole thickness is, most of time, unchanged compared to Barefoot and, with a great nimbleness.

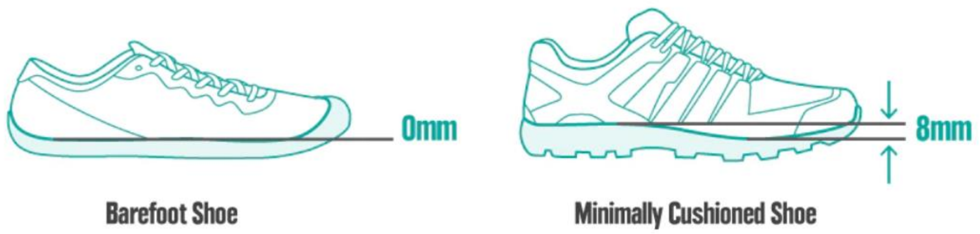

Figure 4.1: *Representation of Barefoot running shoe (0 mm of drop heel-to-toe) and the minimally running shoe (max 8 mm of drop heel-to-toe) used in trail running and their cushioning drop in midsoles.*

4.2 Conventional or Traditional Running Shoes

"Conventional" or ***"traditional"*** is a term used to describe the intermediate class of footwear that lies between minimalist and maximalist. Unlike minimalist, they are considered stiff, with a rigid sole and decently pronounced arch support, including heel elevation, toe spring and toe box taper. Conventional running shoes are often designed with some cushioning and good torsional rigidity (i.e., the shoe should not twist easily), especially under the heel, which helps the body absorb the inevitable heel impact when running on hard ground. On the other hand, a higher cushioning thickness increases the separation between the foot and the ground.

Because of higher cushioning than minimalist shoes, the stack height is usually between 10 - 25 mm and the weight in the range of 170 - 350 g. *(Figure 4.2).* Typical "conventional" shoes have a large heel-to-toe drop, 10-12 mm, but it is not uncommon to find shoes with a drop of more than 12 mm [13]. In addition, conventional shoes are usually narrow at the toe, leading to frequent and painful deformities of the fingers *(Figure 4.3)*.

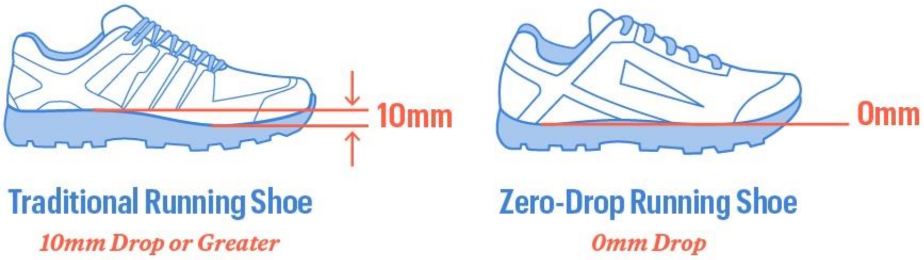

Figure 4.2: *Representation of Conventional Running shoe heel-to-toe drop (left) and the Minimal Running shoe heel-to-toe drop (Zero-drop shoe) (right) in not defined shoes brand.*

Figure 4.3: *Representation of foot geometry when it is inside a "Minimalist or Barefoot" (left) shoe compared to a "Traditional or Conventional" shoe (right).*

4.3 Maximalist Running Shoes

"Maximalist", or super-plush shoes, is a term used to describe shoes that are not necessarily the opposite of minimalist shoes, but are generally shoes characterised by a wide midsole, a stiff sole, great cushioning and a rocker effect on the foot. Usually, they can be identified by the midsole looking bulky and too big for standard shoes [14]. The main difference between Maximalist shoes and the other groups is the oversized stack height, which is usually over 30 mm. The higher the stack height, the more cushioning. Since many runners tend to land on their heels, a cushioned shoe can provide enough support to prevent heel slippage and better absorb the impact of any foot strike on the legs, knees and feet.

However, the heel has a slightly higher stack height than the forefoot. Especially in recent years, the equal stack height of the heel and toe stack height, characteristic of "minimalist" shoes, has become one of the most important features of maximalist shoes. Even though the average runner tends to strike more in the heel, the cushioning of the entire midsole is sufficient to absorb the impact on the ground, even without a thicker heel stack *(Figure 4.4)*.

The high protection of the feet from hard and unyielding surfaces is provided by the higher sidewalls compared to other types of shoes, which increases the recovery run and the comfort of the feet.

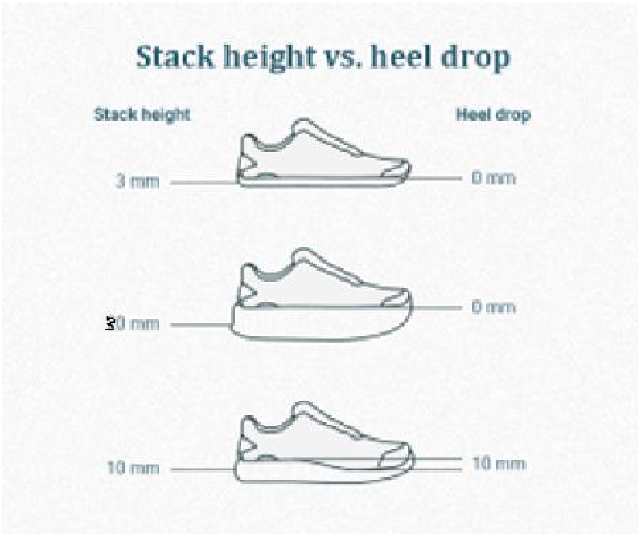

Figure 4.4: *Comparison between Stack height and Heel drop in Minimalist (top), Maximalist (middle) and Conventional(bottom) Running Shoes.*

4.4 Comparing Minimalist, Conventional & Maximalist Running Shoe characteristics

4.4.1 Kinetics and Kinematics Characteristics

In the literature, it is usually intuitive assumed that a change in midsole thickness and heel-to-toe drop would lead to a different performance [59]. According to the previous considerations, there is no better or worse footwear between minimalist, conventional and maximalist running shoes, but one suitable shoe is more suitable than another, depending on the area of applications, surface, physical characteristics and many other factors.

As described earlier, the lower the heel height and drop, the flatter the foot is at ground contact, resulting in a midfoot strike with higher plantar flexion and a greater joint angle at the moment of ground impact [15]. The lower the foot angle at ground contact, the greater the leg stiffness [58,60]. In particular, maximalist shoes have a higher stiffness of the ankle joint, while the stiffness of the knee joint is lower compared to min and conventional shoes [61]. On contrary, higher shoe cushioning encourages the runner to heel strike pattern [58]. Moreover, the pressure and forces in the plantar area of the foot decrease significantly in maximalist shoes, especially in the forefoot area, but also in the entire plantar area of the foot, confirming that foam cushioning absorbs pressure and forces better than a flat midsole

Thicker midsole requires more time to return energy during the propulsion phase, resulting in a longer contact time and a rapid increase in stride length. This finding could explain the increase in forefoot and lower extremity stress fractures that occurred in wearers of minimalist shoes [19]. Instead of lower plantar pressure and force in soft-cushioned shoes (maximalist), the same shoes had a higher vertical impact pressure force. This counterintuitive result suggests that the positive effects of cushioning shoes on injury risk cannot be explained by the attenuation of impact force [17] *(Figure 4.5)*.

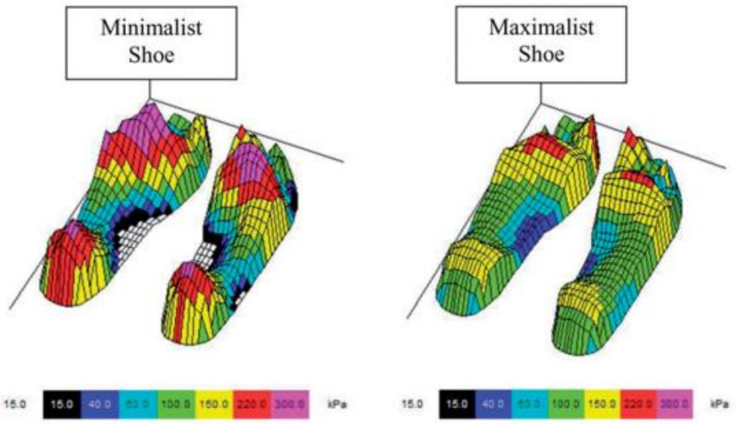

Figure 4.5: *3-D representation of mean peak plantar pressure distribution in Minimalist and Maximalist running shoes.*

In addition, the internal peak tibial damage as twisting and rotation are significantly increased from maximalist to conventional and in the end minimalist. However, higher the cushioning of the shoe, the lower the risk of overpronation movement with a similar risk of injuries compared to neutral footwear [18]. This evidence means that minimalist shoes may place runners at increased risk from chronic injury compared to conventional and maximalist shoes [62]. In conclusion, maximalist shoes develop a lower fatigue during long trail running distance for a raised biomechanical response, that represents a metabolic benefit for the body, increasing the running economy (VO_2 max) [63].

4.4.2 Materials design and Geometric Features

EVA foam has always been the standard material for shoes. Over the years, foam technologies have changed a lot and companies have spent a lot of energy to improve properties such as energy absorption, viscosity and stiffness. Polymer blends (neoprene), additive formulations and manufacturing have been used, but always the same main polymer
At the same time, increased stiffness is potentially unfavourable for long distance and trail running distances and reduces running economy [64].
However, in a large number of available designs, it has been shown that the higher the thickness of the midsole (maximalist), the lower the density, and compliant and soft foam degrades faster than stiff or thin foam. Especially in shoes with a large heel-to-toe drop, the heel is thicker than the forefoot, so the rear sole degrades faster than the front, resulting in less drop.
In conventional shoes and even more so in minimalist shoes with zero drop, the EVA foam is slower to degrade.

Intuitively, aspects of microstructure, such as cell size, affect the stiffness of the polymer and gas compression, thus influencing midsole deformation, but at the same time, relative density and differences in density are extremely important for durability, as smaller sizes and closed cells increase density and thus maintain cushioning and durability [65]. So, without changing the composition of the midsole, it is possible to achieve different properties in different areas of the shoe.
It is often possible to observe a "dual-density midsole", which means that an EVA foam can be combined with a medial support made of thermoplastic urethane (TPU). For example, a dual- density midsole has been found to reduce injury rates [16] *(Figure 4.6)*.

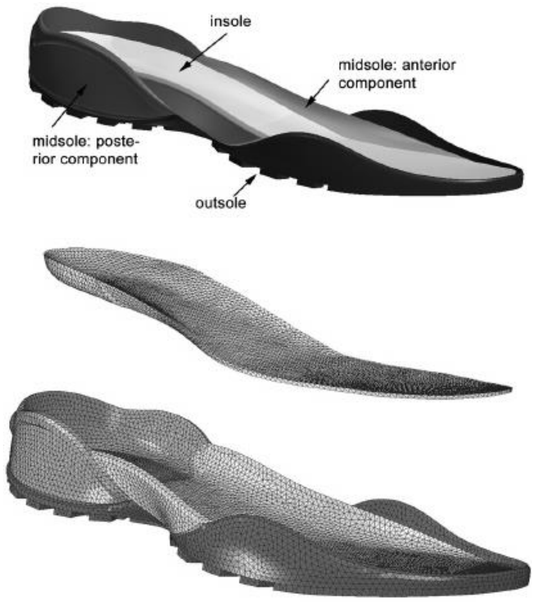

Figure 4.6: *Design representation of footwear soles components and geometry.*

In addition, TPU pieces or EVA incorporated into the midsole could be used in the insole to create arch support with a recognisable crescent recognizable half-moon shape in the midfoot, but this sometimes interferes with the natural flex of our arches, which is important for shock absorption and powerful push-off.

The vertical position and extension of the crash pad do not reduce ground reaction and impact force, while a wider crash pad reduces the dorsiflex angle of the ankle, increases the angle of inversion and stabilises rearfoot function. It has no influence on the maximum eversion of the ankle [66].

The heel opening angle can be adjusted to minimise pronation. Increasing the heel angle decreases the maximum pronation and the maximum pronation velocity.

The shape of the insole has little influence on the running pattern, while the elasticity of the upper material can influence the perceived feeling of comfort. The laces of the shoes improve comfort in the heel width, length and forefoot area compared to elastic shoe covers. The flexibility of the feet when walking is influenced by the elasticity [16,67]. Rocker in shoes is designed to help runners alleviate foot roll during braking and increase running speed [68].

4.4.3 Possible injuries and whole-body effects

As mentioned earlier, minimalist shoes increase plantar flexion of the ankle, improve foot and calf muscle activation, reduce impact loading and, the incidence of stress fractures and knee joint loading, Nonetheless, they represent a potential risk for other types of injuries, such as shin splint syndrome, and they require additional strength in the feet, ankles, calves, quads and even in the core [69].

For trail runners, cushioning is important because they can run longer distances without experiencing calf pain *(Figure 4.7)*.

Cushioning certain shoes may make them more comfortable, mitigate overuse injuries and plantar fasciitis recovery, but it is not necessarily more beneficial for the feet. In fact, elevation at the heel leads to shortening of the Achilles tendon and patella syndrome, shifting the weight of the body onto the fingers and creating poor posture that overloads the pelvis and several areas of the back such as the lumbar spine or neck [12].

People land stronger in maximalist shoes than in conventional and minimalist shoes and have a higher risk of knee/hip/hallux valgus, which is caused by weak arch and toe strength.
However, all shoes with a stiffer midsole in the forefoot, especially from minimalist to maximalist or from soft to hard, increase comfort. In particular, opportunely tuning hardness in the medial/lateral area with a thinner midsole with a lower heel-to-toe drop lead to a more stable temporal activation path of the obliquus vastus medialis and reduce the risk of knee injuries.

Figure 4.7: *Representation of medial/lateral reinforced regions of the midsole of cushioning shoes.*

In addition, it was shown that in a subgroup of runners who suffered from Achilles tendon injuries, increasing the stack (heel) height had beneficial effects [70].

Nevertheless, increasing the heel-to-toe drop (from minimalist to maximalist shoes) the knee adduction increases, but an increased knee adduction is associated to a higher risk of injuries such as patellofemoral pain syndrome, iliotibial band syndrome, and even osteoarthritis.
On the other hand, it’s necessary to consider the training regularity, distinguishing between occasional or unexperienced and regular runners; in fact, it’s recommended a low-drop footwear for less trained runners because encourages a more natural running posture and it helps the “proprioception”, while regular runners appeared to be at higher risk, in particular of bone marrow enema [71].

Chapter 5

Materials, instruments and Methods

This chapter presents the materials, procedures, protocols and analyses analysis used and conducted during the study. A special full-body suit equipped with inertial sensors was used to measure how the body's movement patterns can change when walking with different type of shoes. The procedure and protocols used during the measurement are presented, as well as the implementation of a software programme capable to calculate the Sample entropy and the Lyapunov exponents, in order to understand the differences in the stability and complexity of the movement patterns when running with maximalist or minimalist shoes. Finally, the angles of the lower extremities in the sagittal plane were analysed.

5.1 Footwear Material and Technology

Two different trail running shoes were tested: one "conventional" (Running Terrex Speed SG, Adidas®, or Shoe A) and the other "maximalist" (Altra®, Olympus 4, or Shoe B).

The first, Shoe A, the Terrex Speed SG Adidas® shoe *(Figure 5.1)* with ContinentalTM rubber sole, offers great comfort and performance on dry and wet surfaces. The entire shoe is made from fully recycled materials. With a weight of 225 g, an 8 mm drop and Adidas® Light Strike technology in the midsole, it offers a good balance between cushioning and responsiveness, providing a strong energy return at higher speeds

Figure 5.1: *Representation of the Conventional trail-running shoes used during the test (Adidas® Terrex Speed SG)*

The second, Shoe B, the Altra® Olympus 4 Shoe *(Figure 5.2)* with the Vibram® MegaGripTM outsole of sticky rubber compound and unparalleled grip, offers great stability in dry and wet conditions, robust durability and optimal traction. In addition, the height-adjustable InnerFlexTM midsole made of compression material EVA provides comfortable flexibility. With a weight of 329 g and a stack height of 33 mm, the Olympus 4 offers the maximum cushioning.

Figure 5.2: *Representation of the Maximalist trail-running shoes used during the test (Altra® Olympus 4)*

Load cycles in a fatigue test were used to test the various mechanical properties of these shoes. Each shoe was subjected to 21 load cycles and for each cycle the change in sole displacement was measured load cycles, corresponding to an assumed reference condition sampled every 0.001 seconds.

Under a compressive force, the "conventional" shoe (A) *(Figure 5.3)* shows a maximum displacement of -22.512 mm at the maximum compressive load of -1997 N. In contrast, at the minimum load of -8 N, the displacement is -11.509 mm.
The result of the test shows that the behaviour of the shoe can be described by a hysteresis cycle, namely the friction hysteresis cycle. This specific trend is caused by the viscoelastic stretching behaviour of the polymeric materials inside the shoe sole. Polymer chains show a delay after loading to reach a new equilibrium state during the unloading phase; in this phase, the same strain between the materials requires a lower load. This type of hysteresis is characterised by a counter-clockwise rotation pattern and the area between the lines is the fraction of lost work that is converted to heat by the friction that the polymer chains develop by sliding over each other during the loading period [59].

As already observed in the conventional shoe, the cycle load fatigue test also shows a friction hysteresis loop in the "Maximalist" shoe (B) *(Figure 5.3)* with similar characteristics to the shoe (A). During the loading phase, an almost linear trend between force and displacement is measured. The linearity is quickly lost during the unloading phase.
The maximum compressive load at -1983N shows the highest displacement at -18.57 mm, starting from a value at -1.27 mm, which was taken as a value 0 mm.

Comparing the shoes (Figure 5.3), we can see that the conventional shoe (A) is the stiffer of the two. Undergoing both shoes are subjected to the same load cycle, the maximalist shoe has a larger deformation range compared to the conventional shoe. This means that the greater sole displacement in the maximalist increases' friction between the polymer chains, which dissipates heat and loses more elastic energy during a single fatigue cycle than in the B shoe. Finally, in the unloading phase of the fatigue cycle, shoe A shows a more unstable pattern than shoe B, probably because greater stiffness of the sole causes a greater relaxed micro step of equilibrium for a comparable tension force.

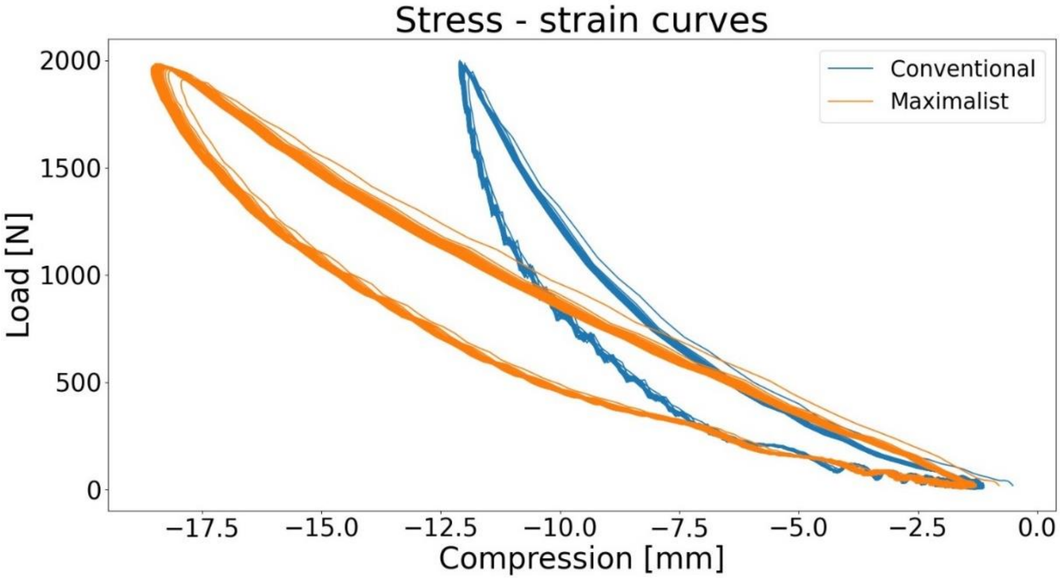

Figure 5.3: *Comparison between Load / Displacement curves after fatigue test for maximalist (B) and conventional (A) shoes.*

5.2 Measurement Instruments

5.2.1 XSens 3D Motion Tracking System

Motion capture is the digital process consisting of recording and analysing human movements. It can be used in various research areas: Sports, medicine, ergonomics and robotics; but it has also found a significant place in cinema: as animation, VFX, virtual reality and training & simulation. In filmmaking and game development, for example, the system is used to record actors' actions for animation or visual effects.

In this study, Xsens 3D Motion Tracking was used to analyse the biomechanics of human walking behaviour. Plot and data series of joint angles and segment acceleration variations provided by the system are considered to compare the stability of running gait between minimalist and maximalist shoes, depending on possible inversion and eversion of the ankle.

XSENS SOFTWARE

Version "MVN Analyse/Animate© 2022.0" (installed on an ACER SWIFT SF314-52 laptop) *(Figure 5.4),* which is used to monitor or record human movements in real time thanks to a virtual avatar; it detects small movements and twitches. The output supports extensive sensor data, segment kinematics, global segment positions and joint angles. The highly detailed dynamic system motion data is made possible by the "MVN Links", which has a sampling frequency of 240 Hz, operates at 64 bits. The raw signal obtained during the measurement is filtered with a low-pass filter, to remove noise from the output signals; later it is converted into diagrams and analysed. Most muscles have a vibration frequency between 6-10 Hz, excepts for the eyelids and tongue, presenting somewhat higher frequencies. Therefore, the literature sets the upper limit of signal filtering at 12-14 Hz [72]. After processing through filtering, numerous different diagrams are produced: Joint angle, acceleration, alignment, position, angular acceleration, velocity, angular velocity, contacts, alignment and acceleration of the free segments. in last stance, the position, velocity and acceleration of the centre of mass are also displayed graphically.

The measurement software requires, as input, the body measurements (foot or shoe length, shoulder height, shoulder width, elbow span, wrist span, arm span, hip height, hip width, knee height and ankle height) of the subject to reprocess the video file and to apply the correct biomechanical criterion for the specific participant.

The reprocessing process, the system to avoid body measurements and motion artefacts, is called "HD Reprocessing". It results in very high-quality motion capture data. Thanks to the filtering process implemented directly in Xsens Analyse© [81], the motion capture data is taken to a whole new level of accuracy and smoothness

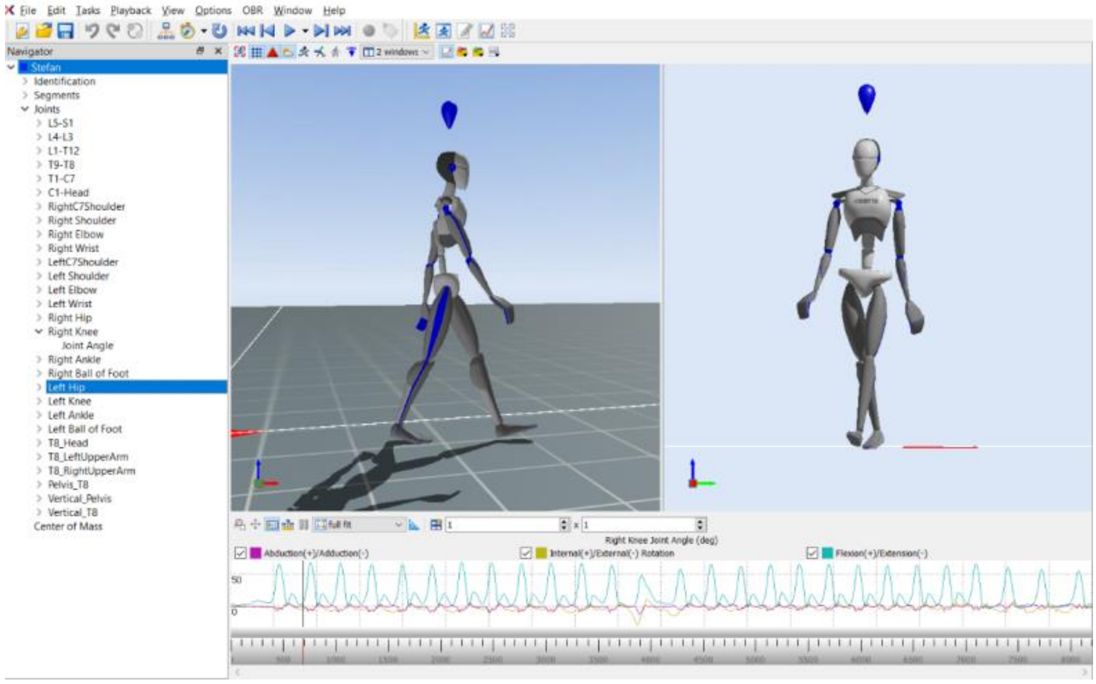

Figure 5.4: *Representation of interface of the software MVN Analyze/Animate in the Xsens 3D Motion Capture System.*

XSENS HARDWARE

The hardware of the system consists by: an XSens suit, an elastic costume made of synthetic fibres usually known by the trade names "Spandex", "Lycra" or "Elastane". It is a polyether-polyurea copolymer with exceptional elasticity. Different sizes are available depending on the participant's body measurements. For example, the suit must be tight enough to hold the MTx sensors (IMUs, size 36x24.5x10mm, mass 10g) in place during the measurement, but at the same time comfortable. On the arms and legs, the suit consists of a double layer to accommodate and protect the MVN Link System (Xsens Technologies BV, Enschede, The Netherlands). This system consists of 17 motion trackers (MTx), each with a specific ID. They are divided into two different types: String Trackers, which consist of three MTx- STR, and single isolated sensors (MTx). The motion trackers are miniature inertial sensors that include 3D magnetometers, 3D linear accelerometers, 3D gyroscopes and a barometer for atmospheric pressure

The measurement units are placed in strategic locations to obtain higher sensitivity to changes in movement for each segment. They are simply attached with Velcro to the suit, which is protected from the weather by a double layer, and closed with a zip. By fixing the sensors in place, possible movement during movement is avoided and possible movement artefacts are minimised. The insulated MTx trackers are located on the pelvis, sternum, hands and head. The MTx- STR's are used to link the legs (thighs, lower legs and feet) and the upper body (shoulders, upper arms and forearms)

On the back of the suit, up to the kidney, are: a body pack (160x72,5x25mm, 150g) and a battery on the right and left side respectively. The body pack is connected to the MTx and supplies power from the battery. It retrieves their data and thus ensures precisely synchronised samples. Data collected is streamed to the PC Access Point via an optimised 2.4 or 5 GHz spread spectrum. The battery (3 rechargeable lithium-ion cells with a power of 10.8 V and 2.9 Ah) with a maximum operating time of about 9.5 hours is used to power the Body Pack.

The Body Pack and the monitoring laptop are connected via an Access Point, which handles the data traffic between the Body Pack and the computer *(Figure 5.5)*.

Figure 5.5: *Representation of the Xsens 3D Motion Capture System; The suit (A), the MTx's motion sensors (B), the Access Point (C) and the Body Pack (D).*

Finally, the GNSS localisation antenna can be connected to the body pack. It is used to measure local position (longitude and latitude with an accuracy of 1 m and altitude with a maximum error of 5 m), 3D velocity, 3D acceleration, free acceleration, 3D rotation rates, roll/tilt and the 3D magnetic field of the person under examination. All signals are sent from global GNSS navigation networks originating from the Global Positioning Satellite (GPS) of the United States, GLONASS from Russia, BeiDou-2 from China and the European Galileo. The estimated position of the receiver is determined by the "pseudo-range" between the satellites, taking into account possible clock errors between the GNSS satellite and the GNSS receiver.

5.2.2 Treadmill System

The measurements are taken on the treadmill *(Figure 5.6)*. It was activated at a constant speed after the correct speed had been set to keep the participants in the comfort zone of running. It was deliberately chosen to conduct the study indoor thus, it was possible to validate the results that were not obtained on the track. As variables (e.g., the type of surface and its topography) could have influenced results, whereas an indoor setting allows for the isolation of shoes only effects [45,73].

Figure 5.6: *Representation of treadmill used during the study.*

5.3 Measurement procedure and methods

5.3.1 Participants and research design

Eight healthy male runners were recruited *(Table 5.1).* Participants had to run at least 20 km per week and had previous experience of trail running. Also, subjects were excluded if they had any kind of lower limb injury that prevented them from running longer than two weeks in the last three months. Participants were also excluded if they suffered from generic medical conditions (flu-like infections, chronic post covid effects, psychotherapeutic treatments, systemic or other organ diseases, diabetes II, cardiovascular, neurological, psychological and orthopaedic conditions). Medical history was obtained through a self-report questionnaire and eligible participants gave written informed consent prior to the study.

Table 5.1: *Descriptive characteristics of participants and running treadmill speed, represented as mean ± standard deviation.*

	Participants (n=8)
Age (years)	27.3 ± 2.3
Height (cm)	176.4 ± 6.8
Mass (kg)	68.5 ± 5.6
Running Speed (m s^{-1})	3.0 ± 1.1

5.3.2 Anthropometric dates and self-selected warm up

Firstly, the anthropometric data of the subjects were collected. Their body measurements were used (as previously described) in the post-processing of the files to obtain the final data. Participants then put on the suit and the sensors were attached and connected.

During the test, running movements were recorded during all four sessions. Each participant completed four five-minute treadmill sessions at a constant speed in two different shoes, with five minutes rest between each session. The recordings of the sessions were used to investigate the stability of running movements between maximalist and minimalist shoes

In addition to the four sessions, a pre-test was planned to find the comfort zone during running, which was later used in the actual test. Beside the four sessions, it was planned a preliminary test useful to find the running comfort zone, later used during the real test.

Warm-up test, was an important step to set up the sensors, gain confidence in the treadmill to determining the most comfortable running speed, and to determine the comfortable running speed that participants would later use in the test sessions. During the warm-up training, the sensors settled in, reducing potential movement errors during the test and avoiding possible artefacts. During the warm-up training, participants ran in neutral shoes that were different from the two shoes tested.

A specific and reported protocol, a 'self-selected' warm-up programme, was taken as a reference to introduce each participant to the correct comfort running speed. Participants completed a gradual speed session on the treadmill until they reached the third level of fatigue on a subjective scale of 1 to 5, where 1 was barely warming up and 5 the maximum speed during a 10 km test. The initial speed of the treadmill was randomly selected between 2.0 and 2.5 m/s for each participant. Subsequently, the speed was increased in steps of 0.1 m/s every 5 and 10 seconds, until the comfortable walking pace was reached.

Then the whole procedure was repeated, gradually reducing the speed of the treadmill. Starting at a speed range between 0.5 and 1.0 m/s higher than the value reached from the increase step, the treadmill speed was decreased by the same index and interval range during this time until the participant was back in the comfortable walking zone. If the two speed values did not differ by more than 10% when compared, the average speed between the two was chosen for the test, otherwise the entire protocol had to be repeated. The entire procedure usually required between 5 and 10 minutes [74].

5.3.3 Calibration and test Procedure

The calibration procedure began with the neutral position, also called the N-position *(Figure 5.7).* Participants held this position for 4-5 seconds without moving any segments; then they walked around the room as naturally as possible for the next 10-12 seconds and finally reached the N-position again. The calibration status was monitored directly by the laptop and only after the PC's response was "calibration was good" was everything ready for the running session.

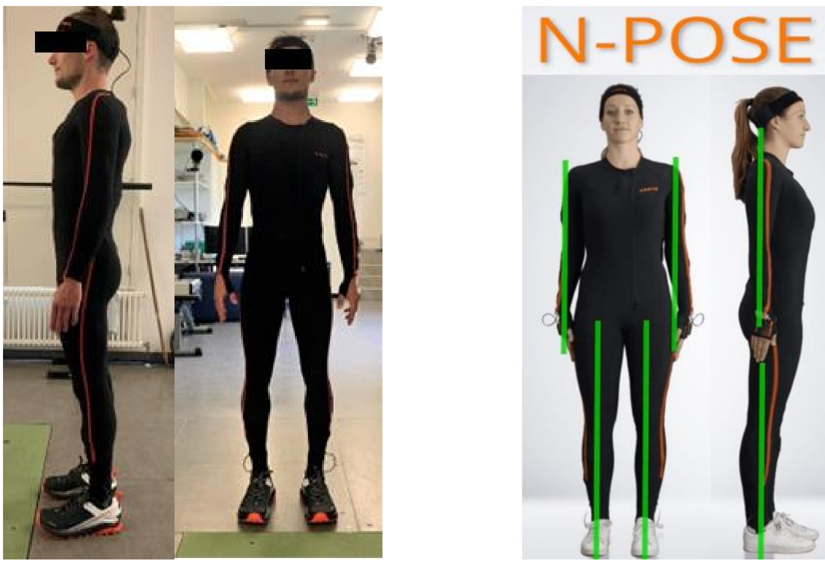

Figure 5.7: *Representation of the N-Pose necessary at the start and the end of the calibration procedure for setting in the right way the sensors system.*

During the N-pose, the participants were still but at the same time as relaxed as possible. Arms were stretched out in front of the chest, palms turned to the sides, legs fully extended and feet pointed forward on one foot in the middle of the track. Afterwards, the participants were free to move around the room before remaining in the N posture again during calibration by the software. To avoid possible sensor movements and artefacts, participants were asked to perform the calibration before each running session after changing shoes.

After the calibration protocol, the participants were ready for the test. The test consisted of four running sessions (two per shoes condition) of five minutes each at the speed chosen during the self-selected warm-up. The order of shoes during the tests was always "ABBA" in order to counterbalance for small fatigue effects. Each activity was followed by a five-minute recovery period during which participants changed shoes, set up the foot sensors again and repeated the calibration process. Each running session was recorded by starting and stopping simultaneously with the treadmill.

5.3.4 Motion, Data and Statistical analysis

Kinematics running were recorded via the inertial sensors of the XSens 3D Motion Tracking System© as previously described, sampling at 240 Hz and calibrated before each session. Data was recorded using 17 MTx sensors strategically placed all over the body and the signal was transmitted to the motion capture software interface.

All sensors were labelled and their signals smoothed on the MVN Analyse© platform in HD mode on NO LEVEL scenario, as recommended for biomechanical application [81]. Angle and free acceleration range (ROM) of the ankle, knee and hip in the sagittal plane were exported for analysis. All motion analysis data were processed using a custom written script on the Python platform (version 3.9.12)

The mean and standard deviation (SD) for each kinematic and spatio-temporal variable were calculated from the central sixty seconds, between the second and third minute of running.

Chapter 6

Results and Discussion

This chapter presents the results and follow-up discussion of the study. It shows the raw, filtered and graphically processed data obtained during the measurement and a possible interpretation of their trend and behaviour.

6.1 Results

The results of this study, without considering the shoe model, shows values of LyE range from 1.07 - 2.41 and 0.77 - 2.16 for the right and left ankle joints, respectively. For the right and left knee, the cut-off values were 2.36 - 4.80 and 2.25 - 4.00, respectively. Finally, the LyE for the right hip ranged from 1.3 - 3.91 and for the left from 1.86 - 3.87 *(Table 6.3 in the Appendix)*.
An average result for each joint and shoe was calculated from the actual raw data, the shoes and the participants, and the distinction between right and left *(Table 6.1)*. According to the LyE ranges described earlier, the average scores for both Maximalist and Conventional shoes in the ankle joint were 1.78±0.24 and 1.62±0.30 respectively; the hip had average scores of 2.84±0.34 for maximalist and 2.67±0.32 for Conventional, while the knee joint reach 3.05±0.16 and 3.24±0.24 respectively *(Figure 6.1)*.

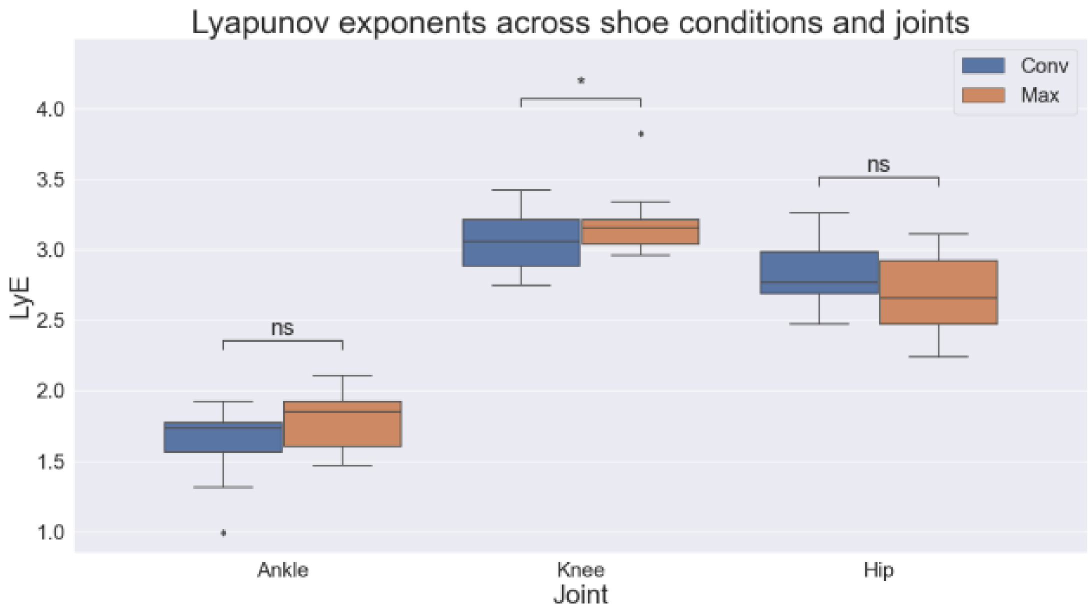

Figure 6.1: *Graph representation of Lyapunov Exponent through two different shoes conditions for ankle, knee and hip joints.*

Starting from the different joints, the variability of the running cycle motion of the limbs was studied considering two different types of shoes: a maximalist (Altra®, Olympus 4) and a conventional (Adidas® Terrex Speed SG); only at the knee joint a significant ($p < 0.05$) difference between the running trajectories was found, with the most cushioning shoe reducing the stability of the motion compared to the neutral shoe. Also, an almost significant difference was found at the ankle, but unfortunately not in a significant way

(p=0.07). Conversely, the stability of the hip joint is not affected by the different shoes, it is not possible to identify specific trends (p = 0,25). Differences between conditions were tested via Wilcoxson test.
However, the value of 1.02 for conventional shoes in the ankle joint and 3.83 for maximalist shoes in the knee were atypical results for those joints because out of standard deviation range.

Table 6.1: *Representation of the average LyE for each participant and total average Lyapunov Exponents values for both shoes and the three different joints*

Subject	**Shoe**	**Avg. LyE**		
		Ankle	**Knee**	**Hip**
1	A B	1,02±0,17 1,46±0,49	2,72±0,37 3,24±0,31	2,67±0,50 2,51±0,28
2	A B	1,72±0,53 1,91±0,18	3,42±0,60 3,83±0,91	3,27±0,39 3,03±0,30
3	A B	1,77±0,30 1,86±0,33	3,14±0,26 3,17±0,25	2,74±0,20 2,70±0,20
4	A B	1,81±0,44 1,85±0,17	3,24±0,21 3,34±0,33	2,79±1,32 2,24±0,21
5	A B	1,75±0,30 1,47±0,26	3,21±0,63 3,17±0,33	3,03±0,64 3,11±0,58
6	A B	1,32±0,36 1,64±0,17	2,99±0,54 3,06±0,19	2,75±0,41 2,35±0,73
7	A B	1,65±0,46 2,11±0,21	2,92±0,28 3,15±0,36	2,97±0,69 2,89±0,33
8	A B	1,92±0,30 1,97±0,13	2,78±0,35 2,96±0,13	2,47±0,44 2,51±0,73
		Ankle	**Knee**	**Hip**
Total Avg. LyE	**A** **B**	**1,62±0,30** **1,78±0,24**	**3,05±0,16** **3,24±0,24**	**2,84±0,34** **2,67±0,22**

Later, as in the analysis of Lyapunov exponents, the complexity of a trajectory running movement was analysed using the Sample entropy. Regardless of the shoes model, results showed that three lower limb joints, the hip joint had the lowest values for Sample entropy for both the right and left hip joints. The values of SampEn ranged from 0.11 - 0.15 and 0.11 - 0.16 for the right and left hip joints, respectively. For the right and left knee, the cut-off values were 0.19 - 0.24 and 0.18 - 0.24, respectively. Finally, the Sample Entropy ranged from 0.12 - 0.34 for the right ankle and 0.09 - 0.28 for the left *(Table 6.4 in the Appendix)*.
An average result for each joint and shoe was calculated from the actual raw data, the shoes and the participants, and the distinction between right and left *(Table 6.2 and Figure 6.2).* According to the SampEn ranges, the average values for Maximalist and Conventional shoes at the hip joint are 0.13±0.01 and 0.13±0.02 respectively; a slightly lower result compared to the ankle (average values of 0.17±0.05 and 0.18±0.05), which is again lower than the knee joint (0.21±0.01 and 0.21±0.01), albeit with a small difference. Surprisingly, this means that the knee represents the joint with the most complex movement, while the ankle, which is obviously

more complex than the joint between the lower parts of the body, again does not have the most complex trajectory. However, the hip has the most predictable and least complex movement, it has the highest self-similarity movement compared to the other two joints.

Overall, it can be concluded that it's not possible to note a significative influence of shoes on joints at any of the three ones considered, ankle, knee and hip *(table 6.2)*. However, an open discussion is focus on the possible influence that filtered data may have on Sample Entropy calculation; the smooth lines of plot represent a possible influence of filtering but, Xsens supply results already filtered without operator check possibility. Differences between conditions were tested via Wilcoxson test.

Table 6.2*: Representation of the average SampEn for each participant and total average Sample Entropy values for both shoes and the three different joints*

Subject	Shoe	Avg. SampEn		
		Ankle	**Knee**	**Hip**
1	A	0,11±0,02	0,23±0,01	0,14±0,01
	B	0,13±0,01	0,23±0,01	0,14±0,01
2	A	0,15±0,01	0,20±0,01	0,11±0,01
	B	0,15±0,01	0,20±0,01	0,11±0,01
3	A	0,23±0,02	0,20±0,01	0,15±0,01
	B	0,24±0,02	0,20±0,01	0,15±0,01
4	A	0,28±0,05	0,21±0,01	0,14±0,01
	B	0,27±0,01	0,21±0,01	0,14±0,01
5	A	0,16±0,01	0,19±0,01	0,13±0,01
	B	0,16±0,01	0,19±0,01	0,13±0,01
6	A	0,14±0,02	0,22±0,01	0,12±0,01
	B	0,18±0,01	0,23±0,01	0,12±0,01
7	A	0,15±0,01	0,21±0,03	0,13±0,01
	B	0,16±0,01	0,20±0,03	0,13±0,01
8	A	0,19±0,01	0,23±0,01	0,13±0,01
	B	0,18±0,01	0,21±0,01	0,10±0,06
		Ankle	**Knee**	**Hip**
Total Avg. SampEn	**A**	**0,17±0,05**	**0,21±0,01**	**0,13±0,01**
	B	**0,18±0,05**	**0,21±0,01**	**0,13±0,02**

However, the value of 0,28 for Conventional shoes in ankle joint and 0,27 for Maximalist shoes always in ankle were atypical results for those joints because out of standard deviation range. Finally, while knee and hip had a small SampEn dates dispersion, ankle had a really huge dispersion of Sample Entropy results; a larger IQR graph represents how ankle joint complexity can cause great variance between legs of the same participants*,* even if, for sure, Sample entropy is a less accurate that Lyapunov Exponent.

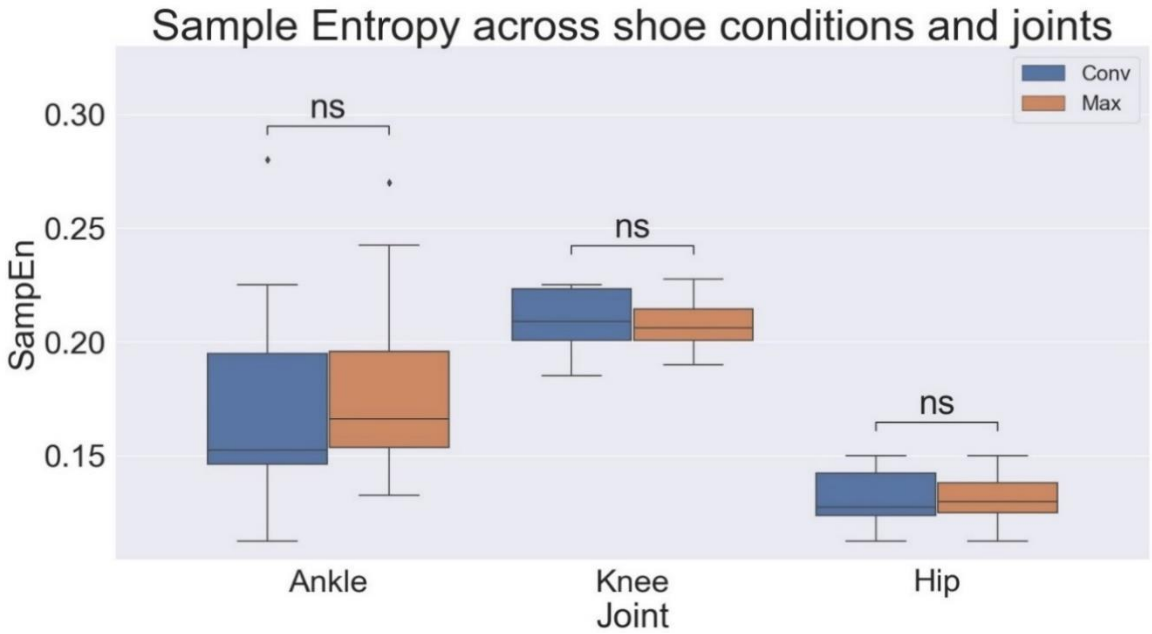

Figure 6.2: *Graph representation of Sample Entropy through two different shoes conditions for ankle, knee and hip joints.*

Moreover, it's also possible, from picture *Figure 6.3,* to purely empirically observe that at the same stance phase time (in the centre of stance phase), the Maximalist footwear, with a higher heel flare angle, reduces the pronation and inversion motion of the ankle during that period, compared to a Conventional shoe with a smaller heel flare midsole. Instead of this result, how previously describe, Conventional shoes show in the ankle an important trend of higher local dynamic stability than Maximalist, and this means that the more pronounced pronation angle doesn't seem to influence the higher ankle dynamic stability during the stance phase. Same thing may be valid for knee but, there is no clear evidence that pronation and inversion motion could directly affect the knee local dynamic stability. In case of a possible direct relation, the pronation and the inversion angle doesn't influence knee stability, because Maximalist footwear is yet more unstable than Conventional one.

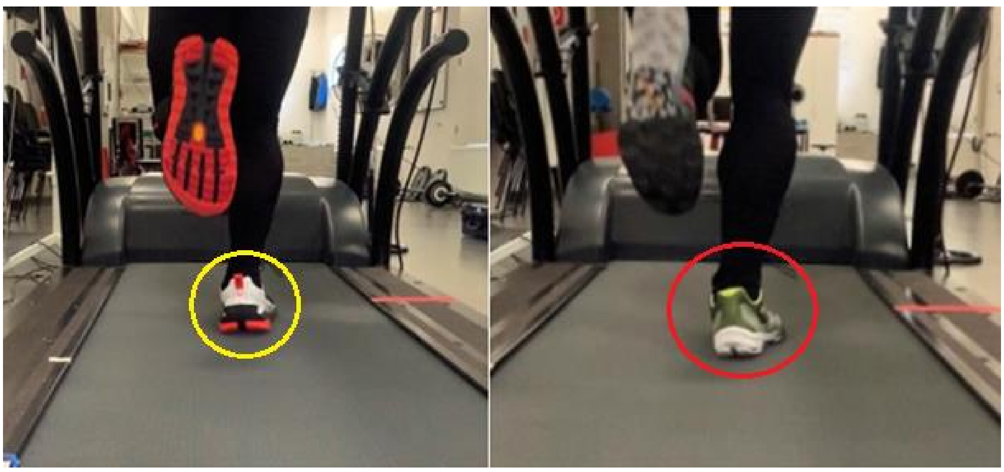

Figure 6.3: *Representation of foot pronation geometry in two different types of footwears on the same participant: Maximalist (Left), and Conventional (Right).*

Despite a similar orientation of the foot, ankle joint angle may be different *(Figure 6.4)*. Even if just an empirical result, contrary to previous studies and counterintuitive solution [15,58], the tester number seven ankle, illustrated below, showed at the foot-strike a lower dorsiflexion angle with maximalist shoes (thicker and flare cushioning sole) if compared to Conventional. The dorsiflexion of foot increased to reach the maximum at the middle stance before turning to the plantarflexion orientation after the toe-off. At the beginning of the swing phase, ankle exhibited the largest plantarflexion, in both traditional and cushioning footwear, *(Figure 6.5)*. Usually, runners touch the ground with rear/middle-foot because the ground force is distributed on a bigger surface. Despite a lower plantarflexion of the ankle joint, conventional shoes, how previously reported, exhibited a more stable running gait. This result, however, should consider the running movement of all participant and not as happened in this case, with just one random tester.

Figure 6.4: *Representation of foot-strike for plantarflexion geometry in two different types of footwears on the same participant: Maximalist (Right), and Conventional (Left).*

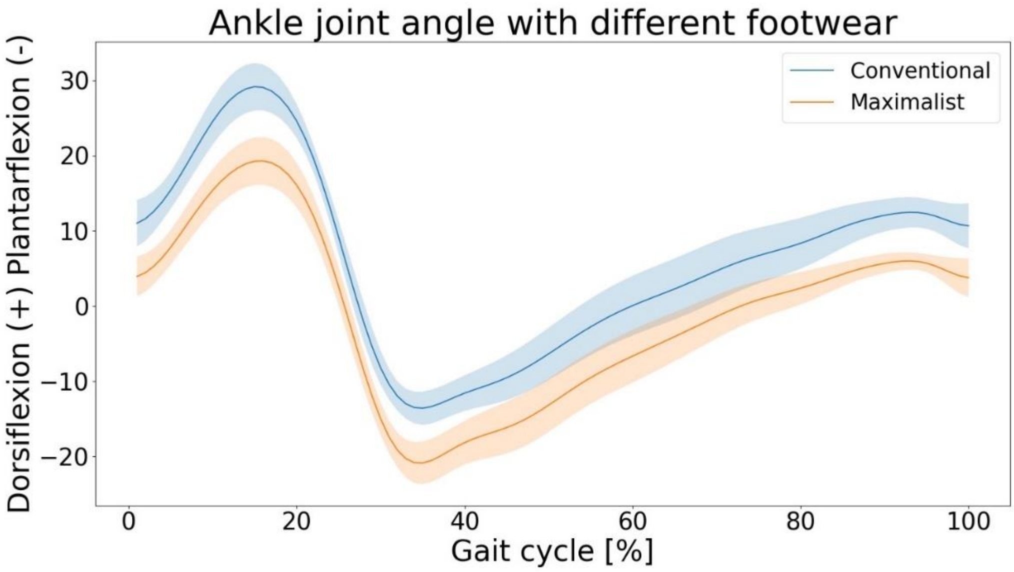

Figure 6.5: *Representation of ankle joint angle in both maximalist and conventional footwears*

In conclusion, the sagittal hip and knee joints angle were not influenced by footwear; maximalist and conventional shoes had similar trends in both joints *(Figure 6.6 A and B)*.

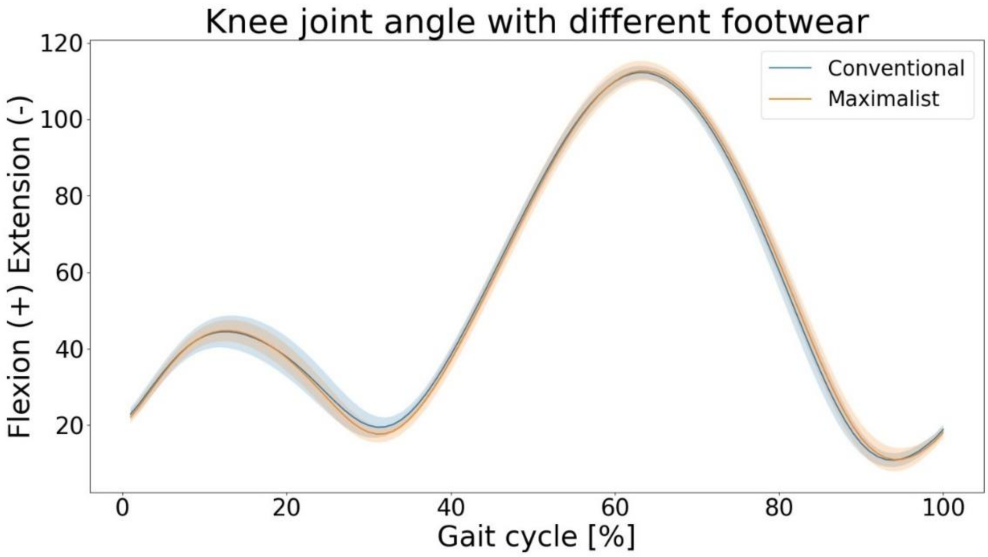

Figure 6.6 A: *Representation of knee joint angle in both maximalist and conventional footwears*

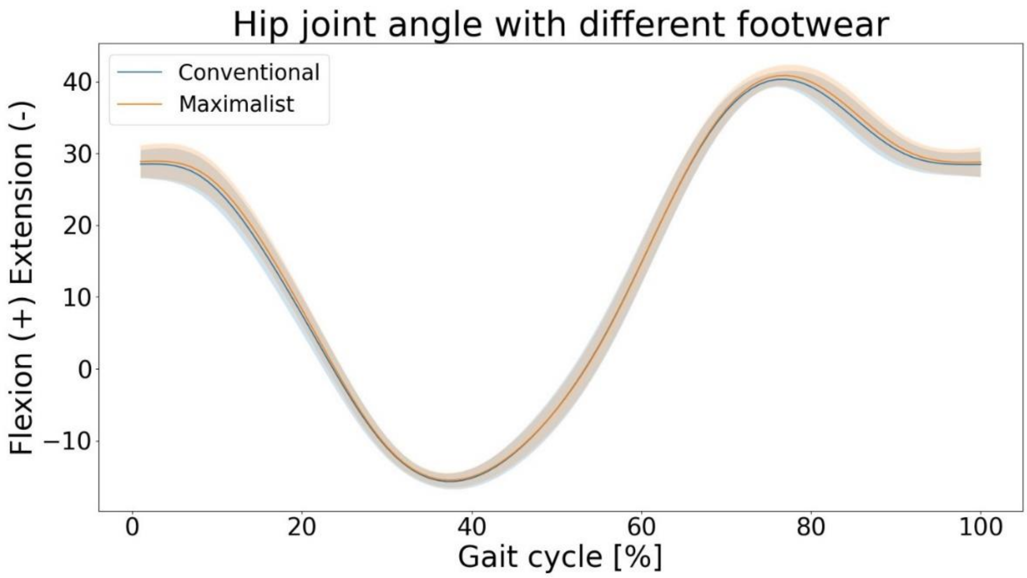

Figure 6.6 B: *Representation of hip joint angle in both maximalist and conventional footwears*

6.2 Discussion

The purpose of this study was to investigate the coordination variability and complexity on ankle, knee and hip (lower extremities) movement in healthy runners, while running on a treadmill, and wearing maximalist and conventional running shoes. Previous studies, that have investigated the influence of Maximalist and Conventional shoes on lower extremities stability and complexity coordination movement, reported conflicting conclusions: a no overall change in stability [75], an overall instability improvement with Ultra-cushioning or Maximalist shoes than Neutral or conventional ones [76,77] while, no one reached a decreasing in stability for conventional shoes compared to maximalist. This study indicates that knee coordinative strategies are affected by footwear.

Running shoes with a lower heel drop and cushioning sole (Adidas® Terrex Speed SG) were found to statistically significantly increase the local dynamic stability at the knee, while there was a strong trend even if not significant, at ankle.
Ankle has always received more attention compared to knee and hip joint. In particular, knee was always assumed as ankle and hip intermedial conjunction; a point of coordination stability and complexity trend inversion. Contrary to what it thought, while hip didn't show different rection to different shoes, knee is heavily influenced.
Most likely, the larger Lyapunov Exponent reached in a softer and higher shoe midsole is due to a higher deformation, absorbed and released energy, different hysteresis cycle, but same materials for thick and thin midsole *(Figure 5.3)*. A thicker midsole is softer than a thinner one because the material is the same for both shoes but, geometry of EVA cells was different; it was less dense and quite porous; under cyclic stresses of fatigue a softer midsole experiences a larger strain with a bigger hysteresis cycle and faster degradation. Inside a cushioning midsole, polymerics chains with a viscoelastic behaviour, they are father to each other if compared to neutral sole, needing more time to slide and reaching a new equilibrium state (bigger hysteresis area for maximalist shoes). Presumably, this slower evolution of equilibrium states may cause a reduction in ankle joint control movement, direct influencing knee and resulting in a lower stability motion [15].

Also, conventional shoes, with a thinner midsole, decrease the amount of movement instability by increasing the "proprioception": the perception and the feeling of the foot on the ground at the ground impact and stance phase [75] permitting kinematic adjustment to legs according with the severity of the perceived impact [78]. A shift of the first impact forward, to the middle foot, and consequence ankle, calf, tibial and knee surrounding musculature reactions between traditional and maximalist footwear may be responsible for the knee and ankle new stability and coordinative strategy. Despite a thickness platform difference between maximalist and neutral shoes of just 1 cm, it represents a condition severe enough to cause a change.
The ankle coordination and stability strategy, adopted in traditional shoes, is less dependent on the subtalar joint, and more inverted; the dorsum of the foot may play an important role to control the variability of movement [15]; because a bigger area of contact with ground reduces the opposite reaction force on the foot, a more plantarflexed ankle could represent a key factor for stability and complexity running movement. In addition, a smaller heel flare angle for conventional footwear increases pronation, a movement that apparently doesn't influence stability of running cycle motion. Unexpectedly, ankle joint angles are quite different between Altra® Olympus 4 and Adidas® Terrex Speed SG footwear.

The significant variability in running movement caused by shoes with same insole but different midsole alters the neuromuscular control strategies of the more proximal joint in young and adults. Knee seems to be adopted as dominant joint strategy, rather than an ankle dominant intersegmental coordination strategy [77].
Often neglected, the different mass between "Max" and "Conv" footwear, 329g and 225g respectively, due to the bigger sole in cushioning shoes than traditional may play a significant role, increasing instability and complexity, due to the reduced proprioception.
Differently from expectations, the hip joint local dynamic stability doesn't show clear and significant differences between different shoes.
Overall, the Altra® Olympus 4 middle shoes results in a lower local dynamic coordination to the lower body extremities with a larger Lyapunov exponent.

Complexity of movement was evaluated through the Sample Entropy. All three joints (ankle, knee and hip) don't experience a significant complexity movement variation with the two different footwear. The reason why this happen could be related to a small accuracy of SampEn mathematic tools. Anyway, stability of movement doesn't mean less complex. However, ankle has always been considered the most complex joint, it has the most stable and less complex coordination movement between lower limb conjunctions.

Finally, it's important to consider the several limitations of this study. Treadmill doesn't represent the most common surface where footwear is normally used. A smooth surface my mask the differences in cushioning properties respect to an uneven land. Participants run to a preferred pace according to their fitness level and running experience level [79]. It is unknown how much the divergence of the attractor in Lyapunov Exponent is influenced on the treadmill compared to the over ground. It has been used only a pair of shoes for each family that is studied, conventional and maximalist. However, the LyE method requires only 15-25 continue steps to have a reliable and constant value [80], and we collected one minute of running, it may not fully represent the performance of shoes and runners during an entire trail; participants could need more time of adaptation. A small range of participants took part to the test due to just one shoe size: 8.5 / 42 EU. Pictures and graphs of sagittal pronation, inversion and plantarflexion movements should be representing a larger sample of participants.

Chapter 7

Conclusion

Our approach to understanding if and how different footwears influenced the coordination strategy, stability and complexity in the sagittal plane at the ankle, knee and hip was fixed by the principles of dynamic system theory. Two mathematic tools as Lyapunov Exponent and Sample Entropy were used to evaluate running trajectory coordination, stability and complexity of lower extremities segments respectively. All these features may be influenced by external constraints at directly contact with ankle, knee or hip joint. In this study were analysed the influence of two different footwear conditions: Maximalist (Altra® Olympus 4) and Conventional (Adidas®, Terrex Speed SG), on lower limbs joint and segments stability and coordination. The results of investigation indicate that knee and ankle experienced (the first significantly and the second one with a strong trend) a reduced stability while running in Maximalist shoes *versus* Conventional ones. On the other hand, hip didn't show a precise coordination and stability trend, these results are of relevance especially in an uneven surface during trail running task, where the activity on an irregular land is prolonged for a long time and the possibility of injuries raise.
Running complexity motion, studied through Sample Entropy, didn't experience a significant influence in any of the three conjunctions. More in, ankle always showed the less complex trajectory and the more stable motion between joints, even if sample entropy experienced a big dispersion of values compared to the others.
In running trajectory, variability and coordination problem may be cause by different midsole deformation in the different shoes, dissimilar response to the ground reaction impact, different mass of shoes caused by the thicker midsole of the maximalist, polymeric chains behaviour inside the sole, muscular reaction, plantar- and dorsi- flexion and inversion of the ankle.
From a kinematics point of view, the knee and the hip joint angles are not influenced by wearing maximalist or minimalist footwear. On the other hand, ankle seemed to be more inverted and pronated in conventional shoes. Most likely, they have not a negative impact on coordination and stability movement.

Future investigation could consider the direct influence of higher plantarflexion and pronation on knee and hip local dynamic stability and complex movement. Repeating the same test on the ground, it will be to prove the real influence of the midsole deformation and shoes construction in the coordination stability running.

Acknowledgements

The master thesis project was entirely developed at Universitäts- und Landessportzentrum at the Paris Lodron Universität of Salzburg, within the Adidas® PhD project of my supervisor Matteo Genitrini.

A general thanks to all colleagues, university students and people who participated at the study and helped me with their great knowledge, always helpful.
I would also like to thank Prof.essa Ada Ferri for allowing me to do my Master thesis at the PLUS and helping me with her valuable advice and expertise.
A big thank you to my supervisor and PhD: Matteo Genitrini; he was always present and available to help me with this project. We always worked together changing useful opinion during tests.

Finally, a special thanks goes to my family and people closed to me, the best ever. They supported me during these years.

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Appendix

Table 6.3: *Indication of Lyapunov Exponents values for all eight participants in each lower limbs joint (ankle, knee and hip), distinguishing between right limb, left limb and shoe A (Conventional) or shoe B (Maximalist).*

Subject	Shoe	Trial	Right leg			Left leg		
			Ankle	Knee	Hip	Ankle	Knee	Hip
1	A	1	1,07	2,59	2,43	1,14	3,23	2,41
		2	1,1	2,36	2,47	0,77	2,69	3,44
	B	1	1,16	2,97	2,33	1,03	3,17	2,91
		2	1,5	3,71	2,51	2,13	3,31	2,30
2	A	1	2,41	4,28	3,5	1,33	2,97	3,69
		2	1,86	3,41	2,97	1,27	3,03	2,9
	B	1	2,06	2,61	2,9	1,78	3,89	3,38
		2	2,07	4,8	2,69	1,72	4	3,15
3	A	1	2,15	3,14	2,58	1,85	3,33	2,99
		2	1,54	3,3	2,58	1,52	2,77	2,79
	B	1	1,63	3,36	2,45	1,74	3,06	2,81
		2	2,35	3,38	2,63	1,71	2,87	2,9
4	A	1	2,01	3,51	2,16	1,6	3,22	1,86
		2	2,31	3,22	4,75	1,32	2,99	2,4
	B	1	1,78	3,19	2,54	1,7	3,1	2,08
		2	2,09	3,82	2,13	1,82	3,25	2,21
5	A	1	1,5	2,86	2,69	2,16	3,1	3,87
		2	1,78	4,13	2,41	1,57	2,74	3,13
	B	1	1,71	3,33	2,64	1,51	3,39	3,63
		2	1,1	2,67	2,58	1,56	3,27	3,6
6	A	1	1,31	2,71	3,32	1,16	3,74	2,47
		2	1,81	2,52	2,78	0,98	2,97	2,42
	B	1	1,42	2,96	1,3	1,68	3,24	2,91
		2	1,63	2,85	2,46	1,83	3,2	2,74
7	A	1	1,1	2,87	2,98	1,95	2,59	2,29
		2	2,09	3,27	3,91	1,45	2,95	2,71
	B	1	1,81	2,81	2,93	2,3	3,41	3,18
		2	2,11	2,87	3,01	2,21	3,5	2,42
8	A	1	2,29	2,93	2,91	1,6	2,25	2,73
		2	2,03	3	1,92	1,77	2,93	2,33
	B	1	2,09	2,94	2,26	2	3,14	3,59
		2	2,01	2,85	2,23	1,79	2,91	1,97

__Table 6.4:__ Indication of Sample Entropy values for all eight participants in each lower limbs joint (ankle, knee and hip), distinguishing between right limb, left limb and shoe A (Conventional) or shoe B (Maximalist).

Subject	Shoe	Trial	Right Leg			Left Leg		
			Ankle	Knee	Hip	Ankle	Knee	Hip
1	A	1	0,13	0,23	0,14	0,09	0,22	0,14
		2	0,12	0,23	0,15	0,11	0,22	0,14
	B	1	0,14	0,24	0,14	0,13	0,22	0,13
		2	0,13	0,23	0,15	0,13	0,22	0,13
2	A	1	0,15	0,2	0,11	0,14	0,19	0,12
		2	0,15	0,2	0,11	0,16	0,19	0,11
	B	1	0,16	0,2	0,11	0,14	0,19	0,12
		2	0,15	0,2	0,11	0,15	0,19	0,11
3	A	1	0,22	0,2	0,14	0,22	0,2	0,15
		2	0,25	0,2	0,15	0,21	0,21	0,16
	B	1	0,25	0,21	0,15	0,23	0,2	0,15
		2	0,27	0,2	0,15	0,22	0,2	0,15
4	A	1	0,34	0,21	0,15	0,28	0,21	0,14
		2	0,27	0,2	0,14	0,23	0,22	0,14
	B	1	0,28	0,21	0,14	0,27	0,22	0,14
		2	0,27	0,2	0,14	0,26	0,21	0,14
5	A	1	0,16	0,19	0,13	0,17	0,18	0,13
		2	0,15	0,19	0,13	0,14	0,18	0,13
	B	1	0,16	0,2	0,13	0,15	0,18	0,13
		2	0,17	0,2	0,13	0,15	0,18	0,13
6	A	1	0,13	0,22	0,12	0,12	0,22	0,12
		2	0,15	0,22	0,12	0,17	0,23	0,12
	B	1	0,16	0,23	0,11	0,19	0,23	0,12
		2	0,17	0,22	0,12	0,18	0,23	0,12
7	A	1	0,15	0,23	0,12	0,14	0,19	0,13
		2	0,16	0,23	0,12	0,14	0,18	0,13
	B	1	0,15	0,22	0,12	0,16	0,18	0,13
		2	0,16	0,23	0,13	0,15	0,18	0,13
8	A	1	0,19	0,22	0,13	0,2	0,23	0,12
		2	0,17	0,21	0,13	0,18	0,24	0,12
	B	1	0,19	0,2	0,14	0,17	0,22	0,12
		2	0,18	0,2	0,14	0,18	0,22	0.12