Study of the human foot for the design of an anthropomorphic robot foot

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Chapter 1

Preface

1.1 Introduction

The functionality of the foot has been widely neglected for decades in research work concerning bipedal robots. The Institute of Robotics and Mechatronics of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt DLR) definitely considers this to be a serious shortfall. Obviously, the human foot has been studied in many other fields such as podiatry, orthopedics, sports medicine or biomechanics but almost never applied to robotics. As a starting point, this project is intended to collect and enhance information about the foot with a view to understanding its role in locomotion, and especially in biped locomotion.

1.2 Motivation

The quote attributed to Leonardo Da Vinci: "The human foot is a masterpiece of engineering and a work of art" gives us insight into the complexity of the human foot. However, despite its importance, the foot remains the last undiscovered zone of the human locomotion apparatus since both the knee and legs have been more or less fully understood. The dictionary definition of the foot as the lower extremity of the leg that is in direct contact with the ground in standing or walking furthermore highlights our limited awareness of its complexity and functionality.

Considering the plans of the DLR to advance in the field of bipedal robotics, it was considered important to start studying the human foot in details with a view to analyzing the possibilities for integrating an artificial foot onto a humanoid bipedal robot. This was the main motivation for this project within the bionics group at the Institute of Robotics and Mechatronics.

1.3 Objectives, goals

This project aims to increase our understanding of the principles and concepts behind general bipedal legged locomotion. It is approached with an understanding of the human foot as a starting point.
The main objective is to design an artificial foot that will be integrated into a future DLR bipedal robot. Many questions concerning the design of a biologically inspired foot still remain unanswered. How many toe joints does a robot need? Is one toe sufficient? What are the forces acting on the foot? How can we simplify our robot foot? All these elementary questions require answers.

1.4 Structure of dissertation, organisation

In order to assess the biological functions of a human foot, a literature review was initially carried out. This was followed by a comparative biomechanical simulation of different movements using fourteen different models.
Chapter2 gives an overview of the fundamentals related to the project including robotics, bionics, bipedal locomotion and describes the methods used.
Chapter 3 gives an overview of the foot in terms of anatomy, physiology, biomechanics and podiatry. Also included in this chapter is an outline of the relevant literature on bipedal robots and prosthetic devices. Based on mechanical design philosophy and the in-depth details discussed here, a list of simple design questions that need to be answered is formulated at the end of this chapter.
Chapter 4 addresses specific topics related to biomechanical gait analysis and explains the integration of the equipment and software used for this analysis. It therefore describes a biomechanical simulation tool named OpenSim and presents the model comparison results of motion captured movements recorded in the gait laboratory of the TU Munich.
In chapter 5, both the basic principles of the human foot and the characteristics of an 'anthropofunctional' artificial foot are investigated. Finally, with the acquired knowledge of the huan foot from the previous chapters and with the help of a Function Analysis method, simple functions and criteria are abstracted that are aimed at enhancing future artificial foot design.

Chapter 2

Fundamentals

2.1 Introduction

Since it is important to start with a certain ground knowledge, this chapter presents the fundamentals related to the project work and defines common terms and concepts. Firstly, it introduces the DLR, its main research activities and the bionics group followed by an overview of bipedal locomotion and bipedal robotics. Finally, the method and project progress are described.

2.2 The DLR experience in robotics

The German Aerospace Center (Deutsches zentrum für Luft- und Raumfahrt, DLR) was described as follows in the Automatica trade fair that took place in Munich in June 2008:
"DLR is Germany's national research center for aeronautics and space. Its extensive research and development work in aeronautics, space, transportation and energy is integrated into national and international cooperative ventures. As Germany's space agency, DLR has been given the responsibility for the forward planning and the implementation of the German space program by the German federal government as well as for the international representation of German interests. Furthermore, Germany's largest project-managment agency is also part of the DLR.
Approximately 5,600 people are employed in DLR's 28 institutes and facilities at thirteen locations in Germany: Koeln (headquarter), Berlin, Bonn, Bremen, Hamburg, Oberpfaffenhofen(Munich), Stuttgart... DLR also operates offices in Brussels, Paris and Washington D.C.
DLR Institute of Robotics and Mechatronics:
Mechatronics is the highest possible integration of mechanics, electronics and computer science yielding 'intelligent mechanisms' and robots, which interact with the environment. Accordingly the technical basis of DLR's institute of robotics and mechatronics is in the interdisciplinary design, optimization and realistic simulation, but also in realization of complex mechatronic systems and machine-interfaces.
The institute is said to be a worlwide leading institution in applied robotics research with focus on space robotics and technology transfer into industrial and service robotics, surgery and prosthetics. In addition, the institute is actively involved in airplane design and flight control as well as vehicle control and mechatronic design."

Figure 2.1 illustrates some of the experimental platforms mostly used for showcasing the institute's research topics: The mobile humanoid system 'Justin', which has the capability to perform complex manipulation tasks with its compliant controlled lightweight arms and its two four-finger hands. The commercially available multi-sensor five-fingered 'HIT' hand with fifteen degrees of freedom. The DLR crawler, a six-legged actively compliant walking robot. 'ROKVISS', a force-feedback joystick ground-commanded robot present on the International Space Station (ISS). A lightweight robot 'MIRO' for applications in surgical procedures. The new DLR/KUKA (man-

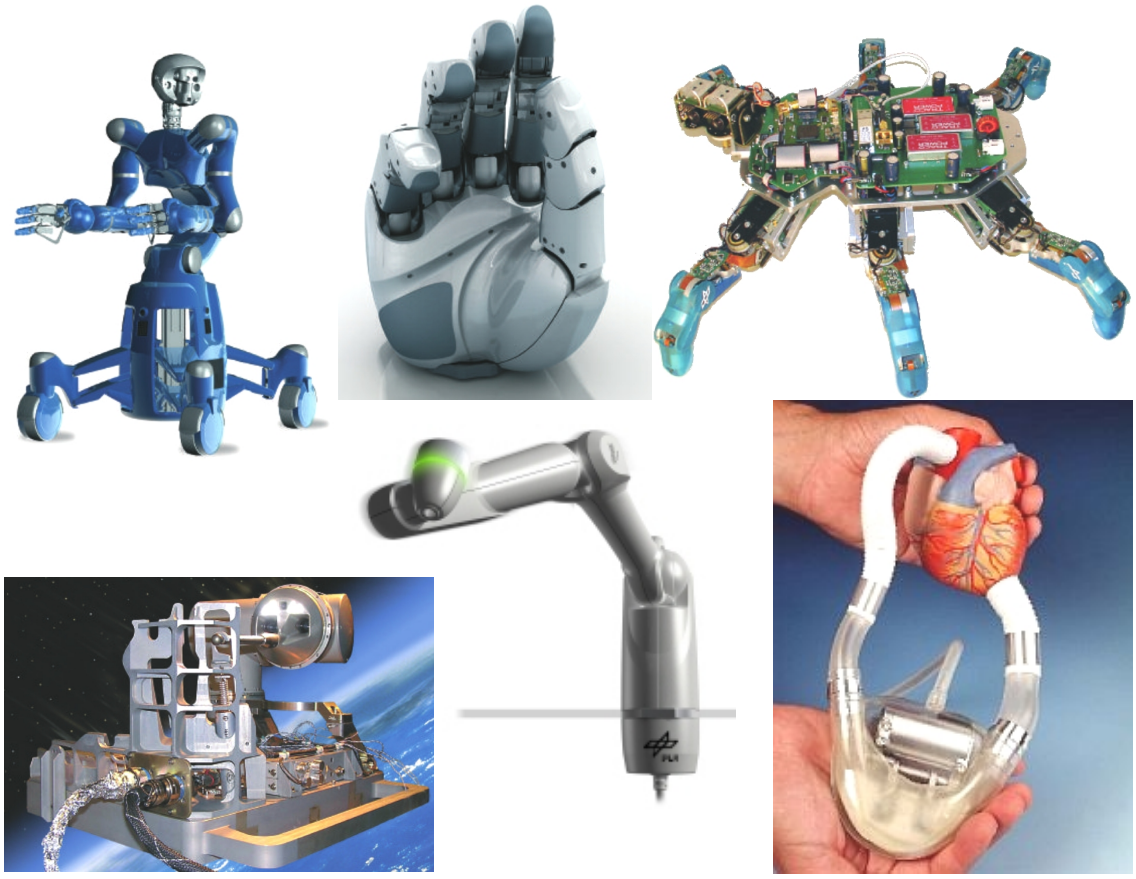


Figure 2.1: Current demonstrators of the Intitute of Robotics and Mechatronics, DLR

ufacturer) lightweight robot committed in the evaluation of safety in Human-Robot interaction. The artificial DLR-Heart, an innovative heart assisting device.

2.3 The bionics group

The bionics group is part of the Institute of Robotics and Mechatronics at DLR. It is a relatively newly formed group in the institute and is described as follows on the DLR website:
"Efficiency and flexibility of biological systems is still unreached in current robotic systems. Biological evolution formed highly specialized systems, perfectly designed with respect to material, force-to-weight ratio and energy turnover. We study human systems in order to improve our robotics.
Although technical hands, such as the highly integrated DLR Four-Finger Hand, can already be used in a large range of applications, such hands are far from offering an alternative to the human hand, because of size and flexibility. Furthermore, a sensor with properties close to those of the human skin is far from being available to robotic hands.
To reach the same dexterity as the human hand, our solution is to construct a precise kinematic model of the human hand using in vivo MRT (magnetic resonance tomography)-data and constructing a model and robotic hand-arm system from that. The resulting robot hand will be very human-like, and can therefore be optimally connected to and controlled by the human peripheral and central nervous systems.
To ensure an optimal connection between robot and human, we investigate various interfaces:
Non-invasive: We concentrate on electromyography (EMG), placing electrodes on the skin to measure muscular activity. This approach is ideally suited for, e.g., active hand prostheses;
Invasive: We investigate a connection to the human peripheral nervous system (PNS) by inserting electrodes into nerve fibres.
In order to deliver sensory data back to its operator we develop an artificial skin-like touch sensor, based on properties of the human sensitive skin.
Biological systems are brilliant regarding their computational efficiency, complexity and adaptability. Therefore, we complete the system by carefully investigating biologically inspired cerebellum-based control strategies."

Current research topics are for example the design of an artificial pressure-sensitive skin, the development of an EMG-controlled robot hand, the examination of human-like ball catching strategy or the study of a precise hand kinematical model.

2.4 Fundamentals of robotics, bipedal locomotion

2.4.1 Humanoid robotics

Over the past decade, several anthropomorphic robots have been constructed. Some of them became well known even for non specialists. Especially Honda Robot 'Asimo', Kawada's humanoid HRP2 and Jogging Johnnie at the TU Munich. Humanoid robotics is a wide research topic with many applications such as gaming robotics, medical robotics or service robotics. Humanoid locomotion studies the movement of robots that have a structure similar to humans. Depending on research topic, different mechanical structures and control methods are proposed.
In spite of more than three decades of research in humanoid robotics, there still remain many challenges. Although there exist a variety of approaches for controlling balanced gait, the walking performance of today's humanoids is still relatively poor. However, even if the motion of current humanoids still appears un-natural, their overall performance is quite impressive and exerts a fascination on the spectator. Improvements are required on both the hardware side and the control side. The design of a walking humanoid robot is very important for the overall achievable

performance of the robot.

Much research has been done on completely passive walking machines. Passive dynamic walkers use earths gravity as a power supply. They rely on special geometry and mechanisms as control systems to achieve gaits very similar to the compass gait. Though they are not robots in the traditional sense, they can give insight into walking machines. A passive dynamic walker relies entirely on passive dynamic motions and thus requires no external power source other than a small incline. Several passive legged robots such as these have been constructed and successfully demonstrated.

2.4.2 Bipedal locomotion

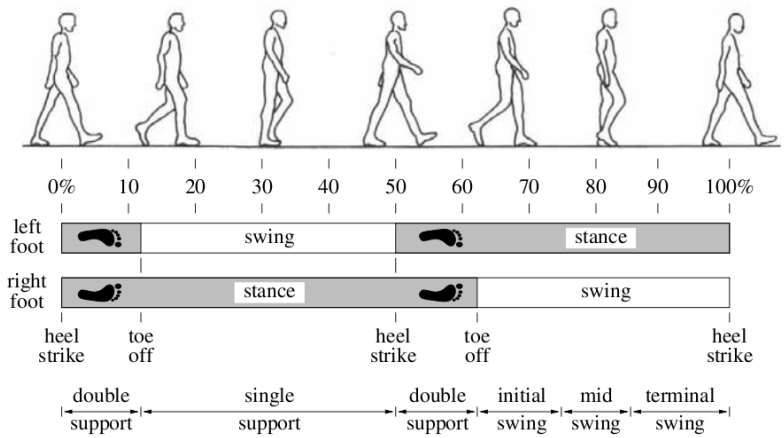


Figure 2.2: Gait cycle illustration

In order to facilitate the study of the human walking gait it is important to understand the complete walking cycle. The beginning of the cycle (0%) is defined as occurring at heel strike of the right foot, which is the instant when the right foot touches the ground, and ends at the second heel strike of the right foot (100%). The cycle is divided into phases depending on events as shown schematically.
The stance phase designates the interval of time in which the foot is in contact with the ground and takes about 62% of the gait cycle period at normal walking velocities. It starts with the heel strike and ends with the toe off. In the remaining time the foot is in the air and not in contact with the ground. This phase is named swing phase and takes approximately 38% of the gait period. The swing phase starts at toe off and ends at heel strike.
A feature of walking as opposed to running is the existence of double support phases in which both feet are in contact with the ground. In running the double support phase disappears giving place to a brief phase in which neither foot is in contact with the ground. The double support phase begins with heel strike and ends with toe off of the opposite foot.

Chapter 3

Literature review

3.1 Introduction

The third chapter of this study is intended to summarize as clearly as possible the main properties, observations and interesting information found during all the project work. One of the main purpose of this project is to take specific knowledge and see how it can be used and transferred to bipedal robotics. Thus, this chapter deals with multiple disciplines such as anatomy, sport medecine, orthopaedics and biomechatronics. It is important for the understanding of the whole study to have a good knowledge of the foot, so that the principles of how the human foot works can be investigated.

3.2 The biological foot

3.2.1 Foot bones

A human foot consists of a total of 26 bones (plus 2 small round bones called 'sesamoids' under the first toe). That makes up, with two feet, about one-quarter of all the bones in a human body. It takes 33 inner-joints (contact between two bones), about 100 ligaments (fibrous tissues that connect bones to bones), about 20 muscles groups and numerous tendons (fibrous tissues that connect muscles to bones) to hold the bones in place and to control its movement in a variety of ways. In literature, the foot structure is often divided into three parts, the hindfoot, the midfoot and the frontfoot (or forefoot):
-The forefoot is composed of the five toes and their connecting long bones (metatarsals). Every toe has three phalanges (proximal, middle and distal phalanges) and the respective two interphalangeal joints, except for the big toe (also known as the hallux) which has only one proximal and one distal phalange. The toes articulate with the head of the respective metatarsal (the connecting long bones). These joints are called metatarsophalangeal joint (abr. MTP). They help forming what is called the ball of the foot under the front of the foot plant, which support half of the weight during walking.
-The midfoot has five irregularly shaped bones (part of the seven tarsal bones). It is connected to the forefoot and to the hindfoot by muscles and ligaments and helps forming the foot's characteristic arch, which serves as a shock absorber.
-The hindfoot is composed of two relatively large bones (the rest of the tarsal bones). It forms the structure of the heel and links the foot to the tibia and the fibula (the two bones of the lower leg).
Figure 3.1 represents a basic diagram of the anatomical structure of a human right foot with the bone names. A line represents an anatomical joint, location where two bones connect.

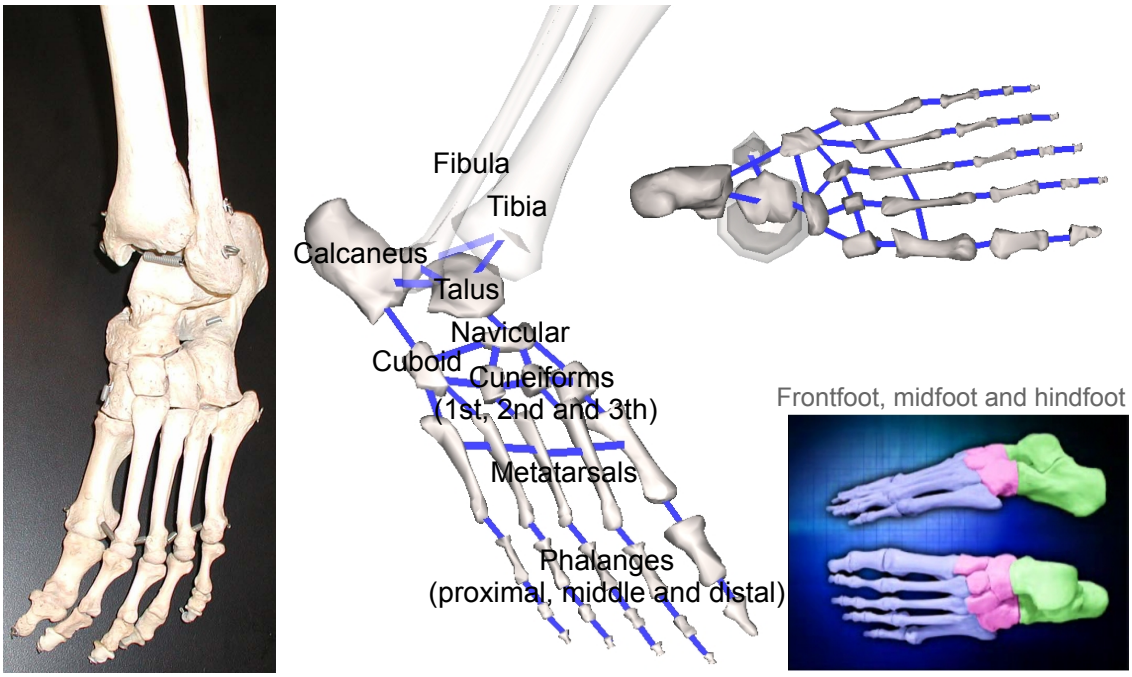


Figure 3.1: Illustration of foot bones

3.2.2 Foot ligaments

The foot ligaments are essentials for the structure of a foot. They are soft tissue that connect two or more bones and help forming a joint. Thanks to their elasticity, they provide joint stability when the joint is under stress. Many small ligaments hold the bones of the foot together (about 100). Most of these ligaments form part of the joint capsule around each of the joints of the foot. There are some very strong ligaments in the foot.

3.2.3 Foot muscles

About 20 muscle groups are dedicated to the foot, which expand and contract to impart movement. Each muscle is defined by one (or many) origin/attachment points and one (or many) insertion/ending points. Intrinsic muscles have their origin and their insertion point in the foot. Extrinsic muscles have at least one attachment point outside of the foot (most of the tme in the lower leg) and only their tendons connect into the foot.
It is not that easy to classify muscles, because of their complexity. There are variations between humans in the muscle positioning (origin and insertion points). Even the number of muscles can vary. Their functions are also not well defined because muscles often have more than just one function (for example when they act together with a synergistic muscle).
Figure 3.2 shows a classification of the foot muscles by location (either as intrinsic or extrinsic) and by functions. Two simple schematic diagrams are also presented for a better visualisation of muscle locations.
The amount that each muscle contributes to accomplishing a given function has not been clearly studied by scientists. The muscle function studies are based on the location of the tendon compared to the axis of the articulations.
Half of the foot-controlling muscles are located in the lower leg (extrinsic) and the other half in the foot (intrinsic). At first glance one would assume that the intrinsic muscles are more dedicated to the motion of the toes (flexion/extension and abduction/adduction) and to the foot arches and that the extrinsic muscles would be generally controlling the ankle and the subtalar joint. However,

* synergistic: function requires coordination with another muscle		**Flexion F Extension E of the ankle**	**Pronation P Supination S subtalar**	**Flexion F Extension E of toe(s)**	**Adducor Abductor of toe(s)**	**Reduce X Thighten V the arches**
Extrinsic (in the lower leg):						
anterior compartment:						
tibialis anterior	TA	F*left	S*			Xmedial
extensor hallucis longus	EHL	F**left	S	E(1)*		Xmedial
extensor digitorum longus	EDL	F**right	P*	E(2,3,4,5)*		Xlateral
peroneus(fibularis) tertius	PT	F*right	P*			Xlateral
posterior compartment:						
triceps surae (calf) (2 gastrocnemius + 1 soleus)	TS	E93%	S after30° of e	ntension		Xlateral
flexor hallucis longus	FHL	E*left		F(1)		Vmedial
flexor digitorum longus	FDL	E*left		F(2,3,4,5)		Vmedial
tibialis posterioe	TP	E*left	S*			Vtransverse medial
lateral compartment:						
peroneus(fibularis) longus	PL	E*right	P*			Vtransverse medial lateral
peroneus(fibularis) brevis	PB	E*right	P*			Vlateral
Intrinsic (in the foot):						
dorsal:						
extensor digitorum brevis	EDB			E(1,2,3,4)		
plantar:						
1st layer						
abductor hallucis	AbH			F(1)	Ab(1)	Vmedial
flexor digitorum brevis	FDB			F(2,3,4,5)		
abductor digiti minimi	Ab5				Ab(5)	Vlateral
2nd layer						
flexor accesorius	FDA			F(2,3,4,5) assi	stFDL	
lumbrical muscle				F(2,3,4,5) assi	stFDL	
3rd layer						
flexor hallucis brevis	FHB			F(1)		
adductor hallucis	AdH			F(1)	Ad(1)	Vanterior
flexor digiti minimi brevis	FDB5					Vlateral
4th layer						
dorsal interossei				E	Ab(2,3,4)	
plantar interossei					Ad(3,4,5)	

Figure 3.2: Foot muscles sorted by location and main functions

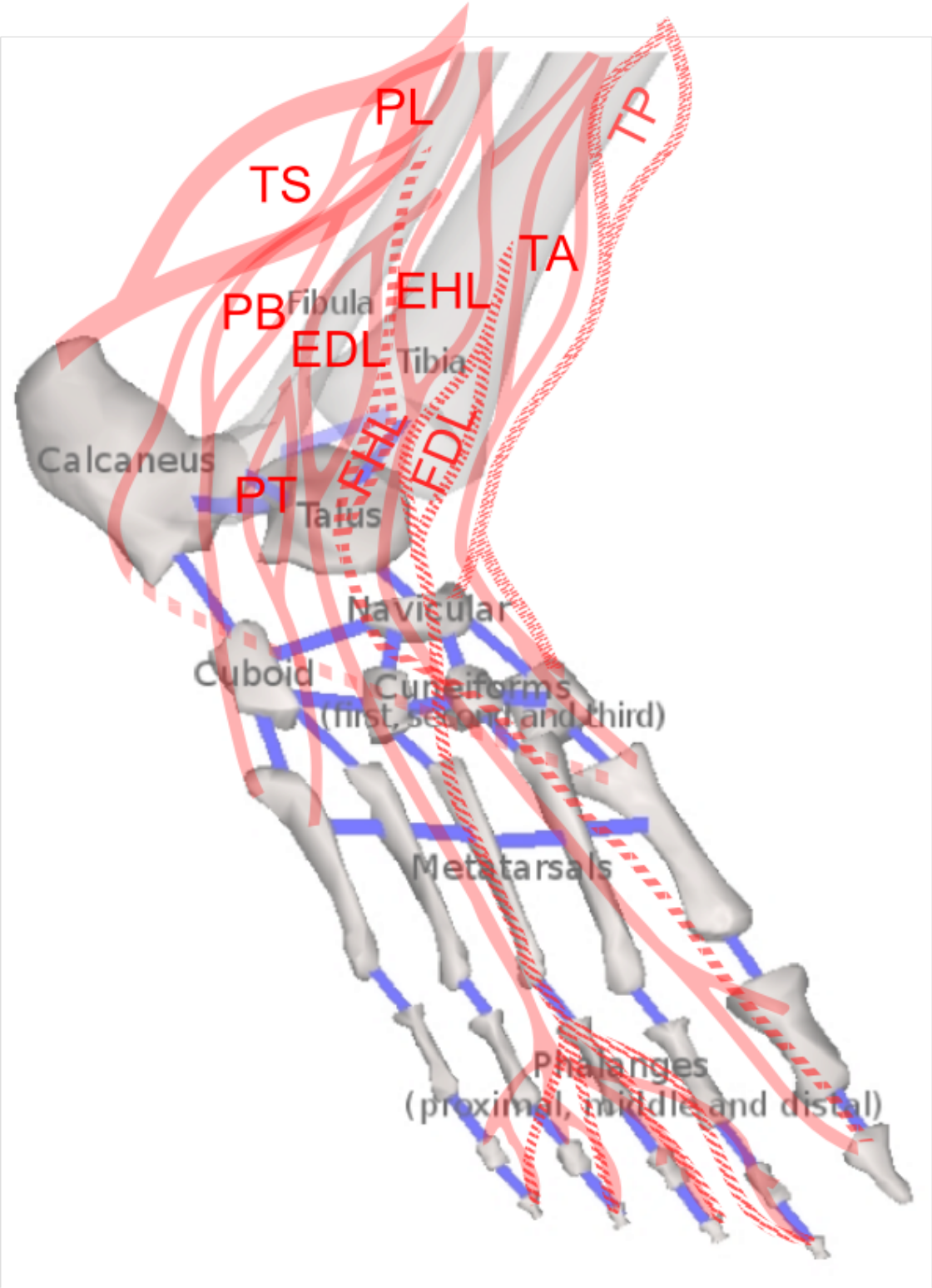


Figure 3.3: Schematic diagram of foot extrinsic muscle location

the mechanics is not so simple. Intrinsic and extrinsic muscles are constantly working together. For example, the triceps surae (TS), which is acting on the calcaneus (heel bone) through the achilles tendon would be useless if nothing were internaly maintaining the foot rigid. A rigid foot creates a lever arm on the ground which propulses the body forward and gives all its significance to the triceps surae. So a foot therefore has powerfull intrinsic muscles without which we simply would not be able to stand.

3.2.4 Miscellaneous

The arrangment of bones, tendon-muscles and ligaments described in the upper section forms the solid structure of the foot, like a kinematic chain. Not to be forgotten is what surrounds this structure: the soft tissue, the nerves, the blood vessels and the skin.
The main nerve to the foot, the tibial nerve, supplies sensation to the toes and sole of the foot and controls the muscles of the foot. Several other nerves run into the foot and primarly provide sensation to different areas on the top and outside of the foot. The main blood supply to the foot is the posterior tibial artery that runs beside the tibial nerve. Other arteries enter the foot from other directions.

3.3 Biomechanics and physiological aspects

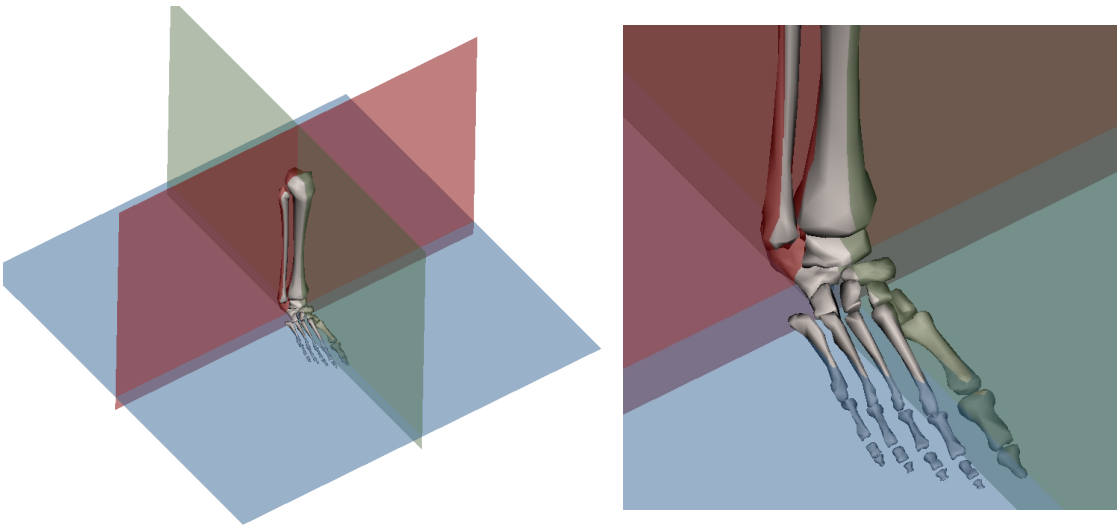


Figure 3.4: The three cardinal body planes: sagittal (green), frontal (red) and transverse (blue)

The body moves in three planes of motion, called the cardinal body planes: sagittal (front to back), frontal (side to side) and transverse (rotational). Many of our joints move, to some degree, in all three planes of motion. The foot is not different.

The ankle-foot complex is a structure which unites 33 anatomical joints (connection between two bones) in the foot and 3 for the ankle at the extremity of the leg. Because the structure is so complex, the character of the motion within the foot is also very complicated. Combined motion takes place in all joints of the foot depending on other joints and on weightbearing. All these joints are exposed to extreme mechanical conditions when the foot rapidly makes contact with the ground during walking, running or jumping. Although there are many joints in the complex, biomechanicians and physiologists consider that there are five main articulations groups.

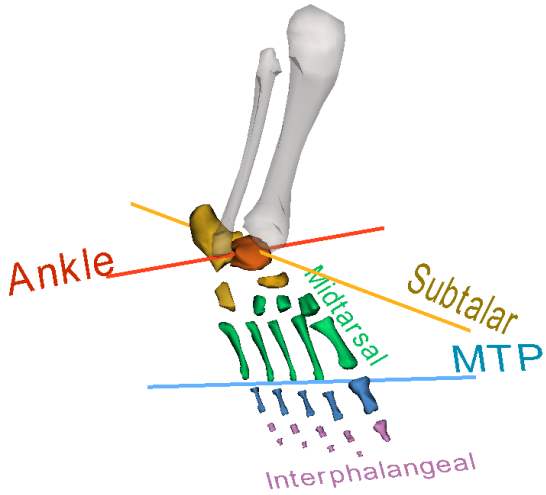


Figure 3.5: Foot main articulation groups

The main articulations are:
-the ankle joint,
-the subtalar joint,
-the midtarsal joint,
-the 5 metatarsophalangeal joint (toes joint),
-and the 9 interphalangeal joints
Figure 3.5 illustrates these five joints. While the ankle is included in almost all models, the subtalar and metatarsophalangeal joints are integrated in relatively few. All three are represented as simple joints (three rotations over three fixed axis). The midtarsal and the interphalangeal joints are rarely described or used. However, they all play an important role in human locomotion, as we will try to investigate.

3.3.1 Ankle

The ankle or tibiotarsal joint controls the movement of the leg relative to the foot and it is essential for walking. It is exposed to extreme mechanical conditions when the foot is weightbearing. It is widely considered by scientists as a one degree of freedom hinge joint, whose motion occurs in the sagittal plane. It is actually more complicated than this.
Figure 3.6 illustrates the articular surfaces of the ankle: first a mechanical view often compared to a 'mortise and tenon' mechanism (used by wood workers to join pieces of wood) and then the corresponding anatomical view with the skeleton surfaces and the three articulations surfaces.
The ankle can be described as consisting of:
-a lower structure, the talus which has on its superior side a roughly cylindrical surface,
-and an upper structure, the end of the tibia and fibula, forming one structure containing a cylindrical cavity corresponding to the talus surface.
The spacial orientation of the ankle axis in relation to the three cardinal body planes is: 8 ° from transverse plane, 82 ° from the sagittal plane, and 20 ° from the frontal plane. With this configuration, we can consider that the dominant motion in the ankle joint is plantarflexion (extension) and dorsiflexion (flexion). The joint axis changes dynamically between dorsiflexion and plantarflexion. During plantarflexion, the axis shifts or tilts slightly in the frontal plane.

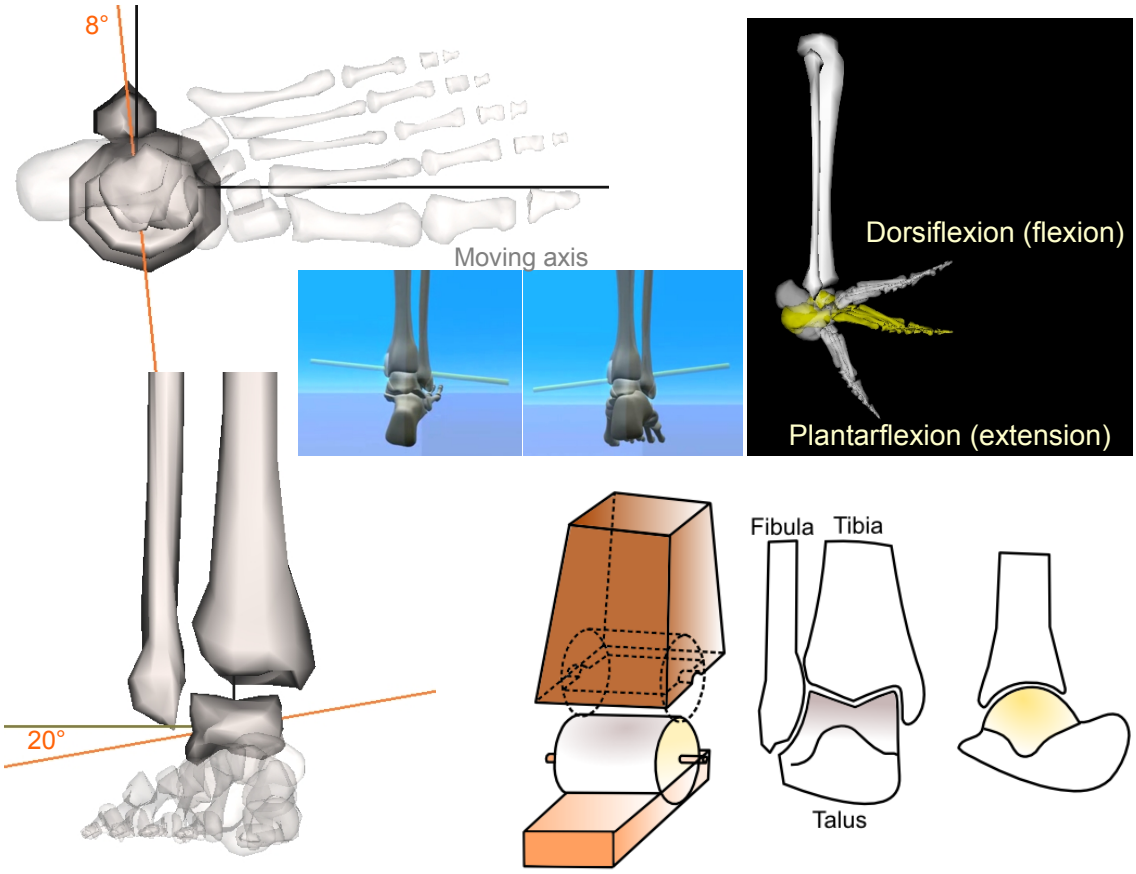


Figure 3.6: Illustration of the ankle joint (involving talus, tibia and fibula): simple axis, moving axis, contact surfaces, motion definition

The range of movements of flexion and extension is determined by the length of the articular surfaces and the ligamentous and muscular factors (very important for stability) and can be deduced to be 70 ° to 80 ° . It can be shown that extension has a greater range than flexion ,respectively 30 ° to 50 ° against 20 ° to 30 ° . The ankle cannot exhibit movements around the two other axis in space. This transverse and frontal stability depends upon the 'mortise and tenon' mechanism of the two malleoli (extremities of the tibula and fibula) and their respective strong ligaments that capsule this articulation and act like a pincer.

3.3.2 Subtalar joint

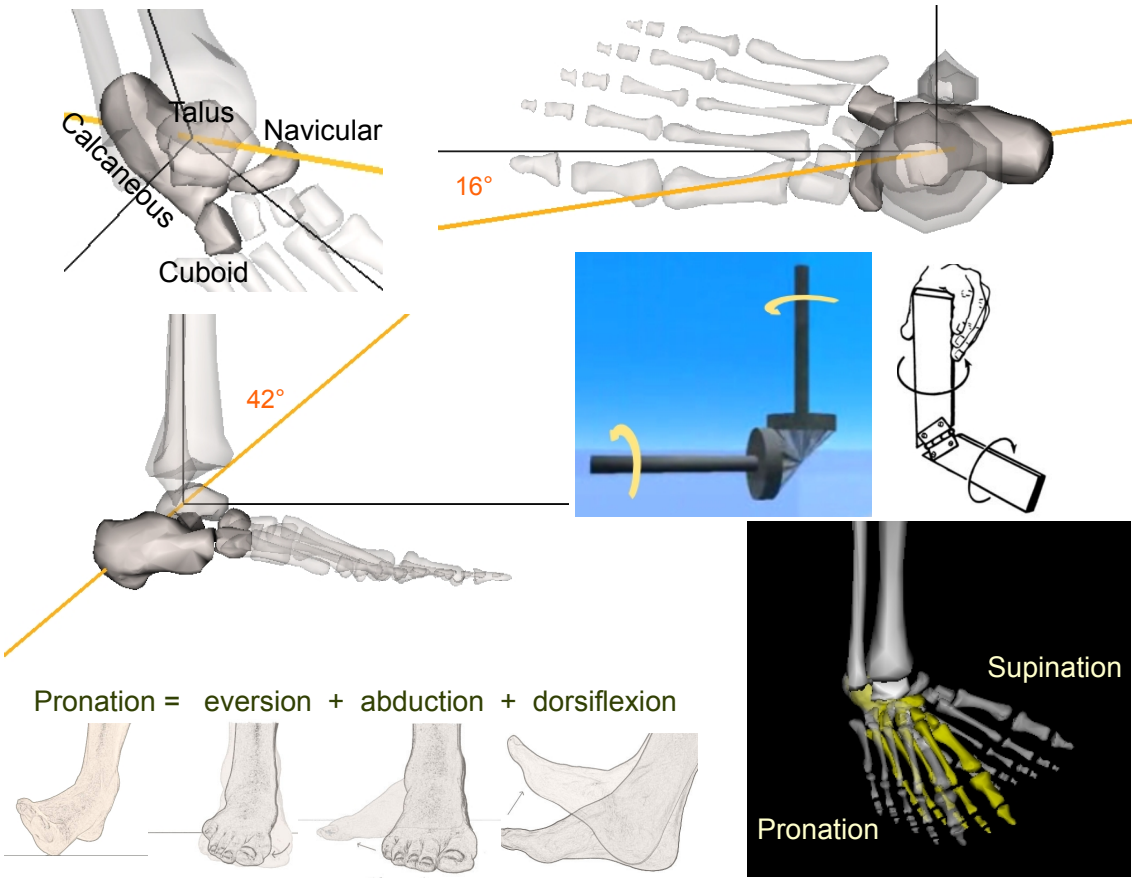


Figure 3.7: Illustration of the subtalar joint (involving fixed talus, calcaneous, navicular and cuboid): functional oblique axis, mitered joint, triplanar motion definition

The subtalar joint, also known as lower ankle or talocalcaneal joint is the meeting point of the talus (ankle bone) and the calcaneus (heel bone). The joint is far more complicated than the ankle.
Basically, it has two or most of the time three contact facets. The corresponding contact surfaces of the talus and the calcaneus are incongruent so that they don't fit together at extreme positions. So it is an unstable joint and therefore, ligaments must provide strong further support to limit the mobility of the articulation. Although the motion of that joint is not fully understood, it is commonly thought of as a functional mechanical hinge joint with a movement occuring about one oblique axis. Rotation about this axis results in a triplanar movement that was first described from clinical observations in 1941 by Manter and was then confirmed by others. This axis not only applies to the subtalar joint but also to the transverse tarsal joint, which is formed by the

articulation of the calcaneus (heel bone) with the cuboid and the articulation of the talus (ankle bone) with the navicular.
Clearly, it represents a combined joint that controls all the hindfoot (4 bones). Biomechanical analysis of the subtalar joint is hindered by the inaccessibility of the talus, which makes locating the joint axis difficult, and by the high degree of intersubject anatomic variation. However for specialists, it seems clear that all these 4 joints constitute an inseparable functional unit, which is often called the subtalar joint, and together form a simple mechanical joint with one degree of freedom about one axis.
There is a large variation of the subtalar joint axis orientation between individuals and also a large variation of its range of motion. In the litterature, the values of 42 ° from the transverse plane and 16 ° from the sagittal plane are often advanced for the definition of the 'subtalar joint' axis. These values were taken from Manter's study, 1941 and had a standard deviations are of 9 ° and 11 ° respectively. In other studies about the axis position, large variations between individuals also exist. The relatively equaly deviation of the joint axis from the transverse and the frontal plane leads to a codominance of the mobility in both planes. Thus, every degree of motion produce in the frontal plane will produce an equal degree of motion in the transverse plane. This relationship is often compared to a mitered joint.
Just like in the ankle, the axis of the subtalar is a moving axis and not a fixed one. During normal walking, the axis moves from an initial to a final position. The nature of motion is highly dependant on whether the foot is weightbearing (known as closed chain, foot fixed) or non-weightbearing (open chain, foot free to move).
Other points are not clearly defined. The terms used to describe the motion that occurs in the subtalar joint by anatomists and orthopedics differ from those used by podiatrists or biomechanics experts. The triplanar (sagittal, transverse and frontal planes) combined motions associated with the oblique axis of the 'subtalar' joint is sometimes described as being an inversion/eversion and sometimes as a supination/pronation. It is common to interchange supination/pronation with inversion/eversion for defining two rotational movements:
-one which allows the foot to face either way
-and the subtalar motion (which contains the first rotational movement plus two others).
Most research papers use the biomechanics/podiatry conventions and terminology. For this reason, the biomechanics terminology will be used here. So the motion in the 'subtalar' joint is defined to be a Supination/Pronation with the different triplanar components being respectively Plantarflexion(Extension)/Dorsiflexion, Adduction/Abduction and Inversion/Eversion of the calcaneus (with talus as reference). This will be investigated later in the role of the 'subtalar' joint.

3.3.3 Midtarsal joint

The motion occuring between the last 5 tarsal bones and between these tarsals and the five long metatarsal bones is rarely and poorly described in litterature. These joints and mostly unified and called the midtarsal joint group. This group contributes to the changes of curvature of the arches of the foot. The movement of the ends of these metatarsal is a result of this joint and changes the curvature of the anterior arch.

3.3.4 MTP joints

The metatarsophalangeal joints (abr. MTP) are the 5 articulations between the metatarsal bones (the five long connecting bones) and the proximal phalanges bones of the toes. They are identical to those of the fingers except that the side-to-side movements of the toes (abduction/adduction) have a far smaller range than those of the fingers. The active extension/flexion has a range of respectively 50 ° to 60 ° and 30 ° to 40 ° . In these joints, the passive extension/flexion, which is essential in the final phase of taking a step, reaches respectively 90 ° and 50 ° . As Bjsen-Moller presented in 1979, the joints axis are now mostly described as being a combined two axes system.

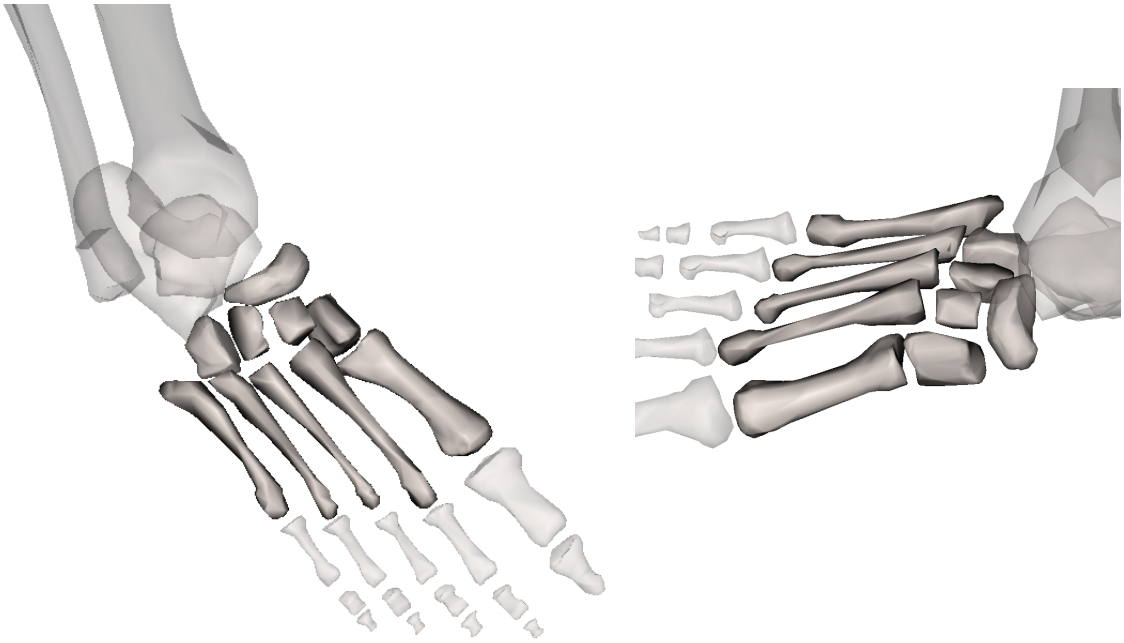


Figure 3.8: Foot midtarsal joint

The first 'transverse' axis is for the first and second MTP joints and the second 'oblique' axis is for the third, fourth and fifth MTP joints. The value of 62 ° form the sagittal plane is used (standard deviation of 6 °) for the orientation of the oblique axis. As you see in the figure 3.9, the oblique axis has a shorter level arm or radius to the achilles tendon and the transverse axis has a longer level arm. The shorter level arm provides least resistance, so it is used to begin unweighting the heel and as heel unweighting progresses, it switches to the transverse axis for the support and the push-off. The weight flow during walking follow this strategy. One consequence of the oblique MTP axis is the supination position of the feet when we stand up on our toes with the heel elevated. One other point that is described many times is the obviously parallelism between the transverse MTP axis and the transverse plane of the cardinal body planes and the parallelism between the oblique MTP axis and a composite axis made of the ankle axis and the subtalar axis as shown in the figure.

3.3.5 Interphalangeal joints

The interphalangeal joints (PIP and DIP joints) are the articulations of the phalanges of the toes. Each joint is surrounded by a joint capsule made of ligaments that hold the bones together. Refering to the muscle diagram, two muscle tendons run along the bottom of each toe that allow to curl the toes, and one tendon runs along the top that raises the toe. The interphalangeal joints are similar to those in the hand. The only movements permitted in the joints are flexion and extension, and the amount of flexion is considerably greater than extension.

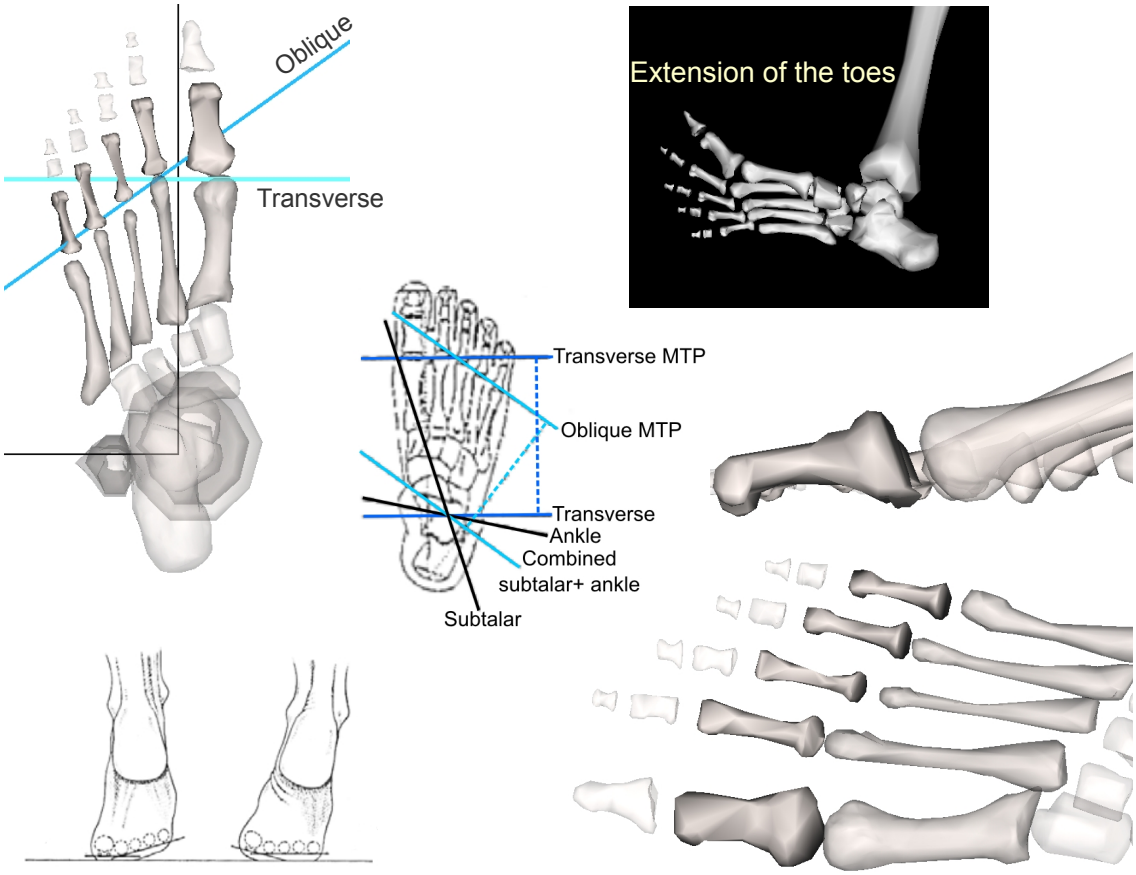


Figure 3.9: Toe MTP joints illustration: double transverse and oblique axis, axis parallelism with combined subtalar/ankle axis and transverse body plane

3.3.6 Foot arches

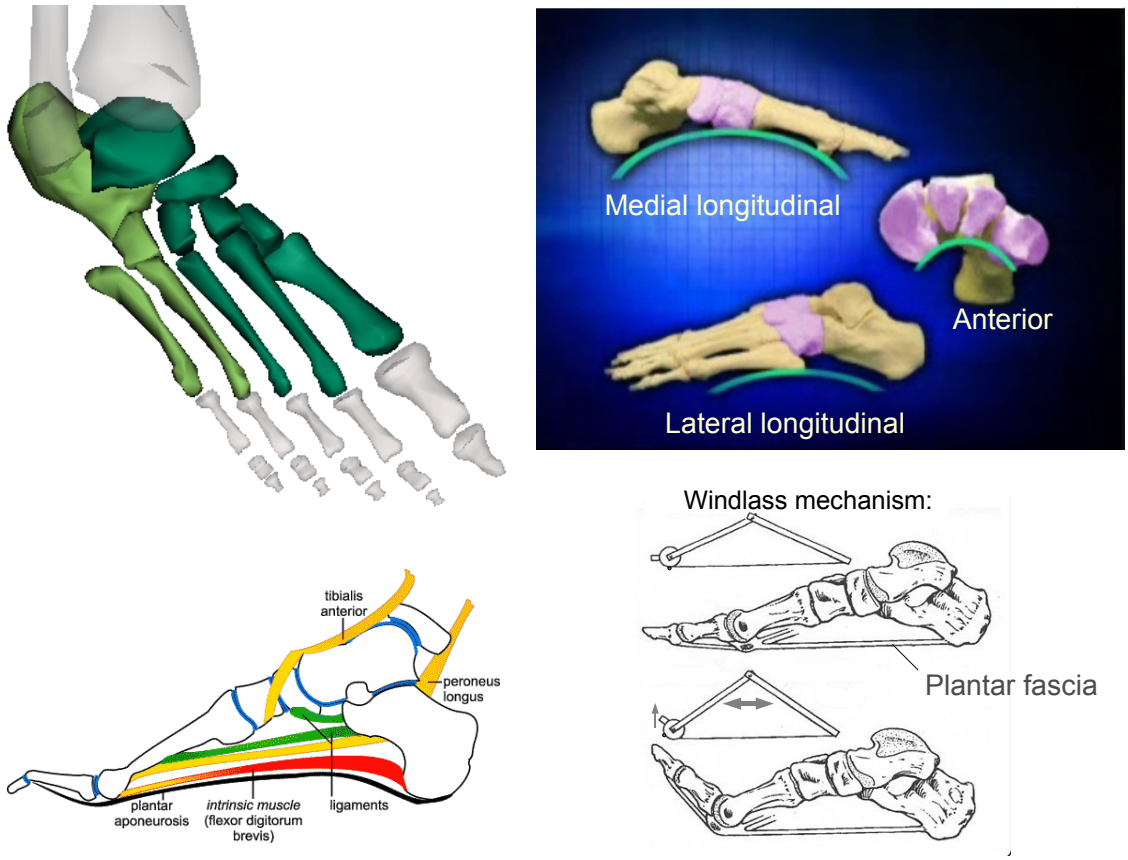


Figure 3.10: Illustration of the three foot arches: bones, muscles and ligaments involved, windlass mechanism

The muscles of the foot are not only responsible for the movement which is made during walking, they also help to maintain the arches of the foot during weightbearing. Our plantar vault is often described as a three arches system. Two arches are arranged longitudinally and one transversely. They are caused primarily by the formation of the bones of the foot and the ligaments which bind them together, and secondarily by the muscles which act upon the bones:
-The first longitudinal arch on the medial side of the foot is the higher one. It forms the instep on a foot-print. It is made up of the first, second and third toes and their metatarsals, the cuneiforms, the navicular bone and the talus.
-The second longitudinal arch on the lateral side is made up of toes four and five and their metatarsals, the cuboid and the calcaneus. It is much shallower than the first medial arch.
-The transverse arch or anterior arch is primarily formed by the 5 metatarsal bones but goes through all the foot. Figure 3.10 illustrates the three arches of the foot.
Every ligament that connects the bones of the foot plays a part in maintaining the arches, but some which pass across two or more joints are especially important. While the relative small intrinsic muscles of the foot also plays an essential part in keeping the arches intact, the long extrinsic muscles which are inserted by tendons into the bones and pass through the ankle have an even more important role. Finally, more superficially in the plant, the plantar fascia (or plantar aponeurosis), a very thick tendon, also plays an important part in maintaining the medial longitudinal arch.
The 'windlass mechanism' is an old, simple and popular engineering concept to move heavy loads.

In the foot, this principle is also used. As the toes move upward (dorsiflexe), the plantar fascia (a very thick tendon in the foot plant) rolls around the toes joints, developing tension. This tension within the plantar fascia packs all the joints of the foot together, the forefoot is drawn closer to the rearfoot. This increases the arch height and converts the foot to a rigid structure. The windlass mechanism principle is described in many fields related to feet study. In shoe design for example, this is the reason why it is important that the toes are allowed to move.

3.3.7 Foot evolution and Foot in animals

Foot evolution in the human is an interesting question. The subject is extremely difficult and not fully understood but several informations can be sorted out. The Humans are plantigrade animals, which means that they stand on the whole foot and not just on the ball of the foot or the toes. This characteristic is not common among mammals and this might come from the fact that both the foot and the hand use to be propulsive and manipulative organs. Consequently, the human foot past through a grasping phase but then the human became a terrestrial biped. Its shape has change to facilitate walking on the ground. For example the big toe has moved in line with the other toes.

Animals can go anywhere, locomoting on substrates that vary in the probability of surface contact, the movement of that surface and the type of foothold present. Basic principles have been abstracted from animals found in nature. The foot is distributed along the whole leg. Distributed foot are very effective for adapting to difficult terrain. Tuned spines exist sometimes along the foot that easily collapse in one direction and provide a foothold in the other direction. Animals add claws for climbing rough surfaces. Actually, to maneuver on all surfaces, animals use hybrid mechanisms including claws, spines, hairs, sticky pads, glues and capillary adhesion. Design secrets from Nature are important: -Distribute control to smart parts, not all in brain, but in tuned foot, leg an body. -Use hybrid solutions, integrated and robust. -Do not mimic nature, be inspired by biology and use these novel principles with engineering solutions to make something better than nature, not designing a copy of any specific foot but a synthesis of the secrets of many feet.

3.4 What do artificial feet look like?

3.4.1 Robot feet

Present robot feet are mostly consisting of a simple rigid plate and one or two degrees of freedom in the ankle. This flat foot design gives extra limitations to the movements of the robot. Several researchers focused on the advantages of toe joints for bipedal locomotion. Heel lifting stabilization, higher step climbing and less energy consumption during walking are the most important advantages. Therefore since the year 2000, most of the recent biped robots started to integrate a basic toe joint. Different kinds of toe joint design have beeb presented since then.

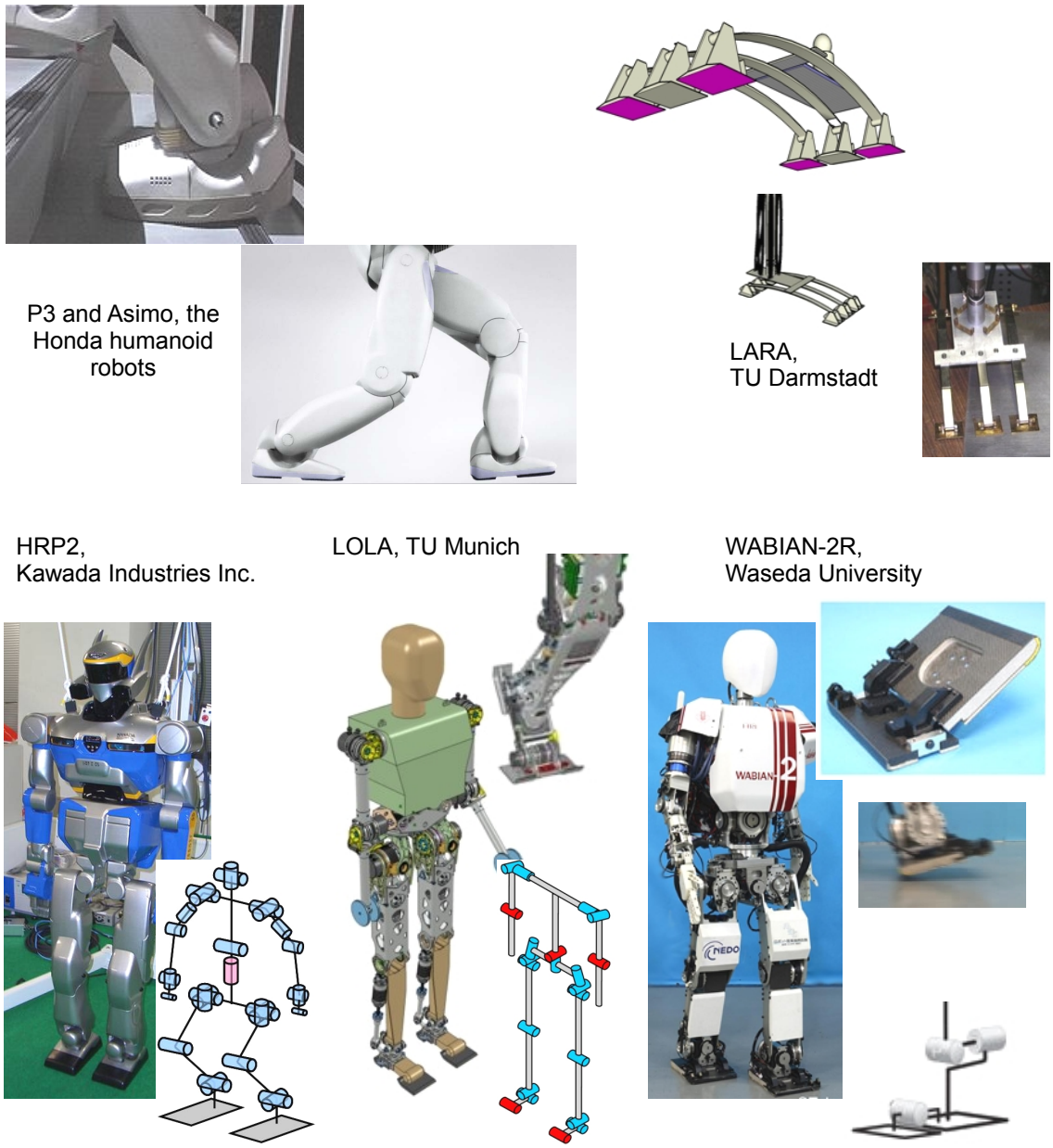


Figure 3.11: Humanoid robot feet

Current bipedal robots with toes have only one. And this toe is most of the time a passive one, it is not directly driven by an actuator. Simple torsion spring systems are currently being tested, where the joint moves only when a force is applied to the toe and obtains its flexibility from a torsion spring attached to the joint. More smoother toe and foot rotations are achieved with spring-damper systems. Even one entirely active toe joint and one hybrid active/passive toe joint are used to achieve faster and less energy consuming walking.
Another interesting point is how the ankle complex mechanism is designed in present robotics. Mostly, conventional robots have 6 degrees of freedom in the leg (3 in the hip, 1 in the knee and 2 in the ankle). The two ankle joints permit two rotations over two axis. The first axis, as everybody would expect, is for doing the extension and flexion motion of the foot and so is placed in the frontal plane. The second axis is always placed orthogonal (i.e. perpendicular) to the first axis in the sagittal plane. It passes through the foot so that the robot can 'roll' its feet (in biomechanics, this movement is called an inversion/eversion). The ankle complex has received up to now little consideration in research on bipedal robots. Therefore, the ankle and more specifically the human subtalar joint will be investigated as it seems to play a important role in walking on uneven surface.
Compared with prosthetics, it seems that the notion of foot flexibility has also been neglected in present robotics. As in the human foot the whole structure plays a role in absorbing schocks, cushion material soles are the only things that give compliance to bipeds, damping vibrations and shocks of landing.

3.4.2 Prosthetic devices

Nowadays, many prosthetic feet are on the market. Prosthetic feet can be divided into two categories, conventional feet and energy storing feet.
One of the most conventional, simple and inexpensive prosthetic foot is the SACH foot. SACH is an acronym for 'solid ankle cushion heel', which refers to the compressible heel that functions as a shock absorber during heel strike.
Looking at the new prosthetics field, we find a completely different approach. Here, the feet are focused to mimic the dynamic behaviour and flexibility of the real foot and to improve or restore the natural lost functions. Since the introduction of the energy storing prosthetic foot some 30 years (also known as dynamic response feet), the modern prosthesis on the market are mostly made from newer materials, such as advanced plastics and carbon-fiber composites and have very ellaborated forms. This makes the prosthetic foot lighter, stronger and more realistic, so that they can passively absorb shocks and release stored energy. This is mainly due to the form of the prosthesis and to the materials used. By flexing a keel or compressing a rubber bumper during heel contact and rollover, energy is stored. Springing back during unloading, it is reusing the energy during the end of the stance phase to improve the push-off. Examples of design are given in Figure 3.12.
Although below-knee prostheses have been commercially available for some time, todays devices are completely passive, and consequently, their mechanical properties remain relatively fixed with walking speed and terrain. Biomechatronics technologies make today's advanced prosthetics, allowing the prosthesis to actively control and automaticaly adapt their functions during certain tasks. Although most of the research and commercial activity has focused on upper limb devices, the development of active ankle-foot prostheses may provide more natural gait than a conventional passive prostheses.

Figure 3.12: Prosthetic devices, from a simple SACH foot (upper left) to the MIT Media Lab powered ankle-foot (lower right)

3.5 Summary and conclusion

In many respects, the foot remains the last unknown link in the lower limb chain. The hip and the knee have been well researched and at the stage where quality joint replacement can be made, it is clear that our understanding of their function is strong. The same cannot be said of the foot. We understand the movement of the four major articulations in the foot (ankle, subtalar, midtarsal and metatarsophalangeal joints). However, we know little of how the small midfoot joints move and how the musculature within the foot acts. It is not clear what role the foot performs as part of the lower limb. Does it simply move as dictated by the structures or can it be more influential in controlling the lower limb?

Chapter 4

Biomechanical analysis of human movements

4.1 Introduction

Biomechanical software that is used for example in gait analysis is envisaged in this chapter to compare different designs. By analysing the simulations of motion captured recorded motion, the role of different functional unit of the human foot is investigate. This chapter discussed the results of the experiments.

4.2 Biomechanical simulation

4.2.1 Biomechanical software

The principal reason for using biomechanical software is that it makes the analysis and simulation of real human movement quite easy. It is therefore possible to analyse what is happening if a basic function of the foot is changed.
The planing of simple experiments revealed that it is almost impossible to interfere directly with the functions of our feet. Many ideas were proposed such as walking with rigid shoes, strapping the ankle or cementing the toes. In the litterature, few papers relate such tryouts (such as for example constraining shoes). It turns out that these solutions are highly questionable since they always interfere with other functions (tactile perception, foot rigidity). Therefore, the main idea of experimenting different 'functional foot design' was progressively abandoned.
Biomechanical software is still very interesting as it enables the analysis not only of foot joint coordinates during a specific movement, but also joint torques and muscle excitations. There are several software packages available on the market but one particular software captured our attention. OpenSim is a relatively new and open-source software created with the help of SimTK, a free centralizing organization to create, share and manage physics-based biological dynamics simulation projects. A list of all existing projects can be consulted on the SimTK website (https://simtk.org). SimTK was developped by Simbios, the National Institute of Health (NIH) Center for Biomedical Computing at Stanford University, USA. SimTK is the home of the OpenSim project, and is described as follows at the URL (https://simtk.org/home/opensim/):

4.2.2 OpenSim

"Overview: OpenSim is an open-source software system that lets users develop models of musculoskeletal structures and create dynamic simulations of movement. The software provides a

platform on which the biomechanics community can build a library of simulations that can be exchanged, tested, analyzed, and improved through multi-institutional collaboration. The underlying software is written in ANSI C++, and the graphical user interface (GUI) is written in Java. OpenSim technology makes it possible to develop customized controllers, analyses, contact models, and muscle models among other things. These plugins can be shared without the need to alter or compile source code. Users can analyze existing models and simulations and develop new models and simulations from within the GUI.
Purpose: Provide easy-to-use, extensible software for modeling, simulating, controlling, and analyzing the neuromusculoskeletal system.
Audience: Biomechanics scientists, clinicians, and developers who need software tools (or code) for modeling and simulating motion and forces for neuromusculoskeletal systems.
Long Term Goals and Related Uses: Provide high-quality, easy-to-use, bio-simulation tools that allow for significant advances in biomechanics research."

4.2.3 Workflow in OpenSim

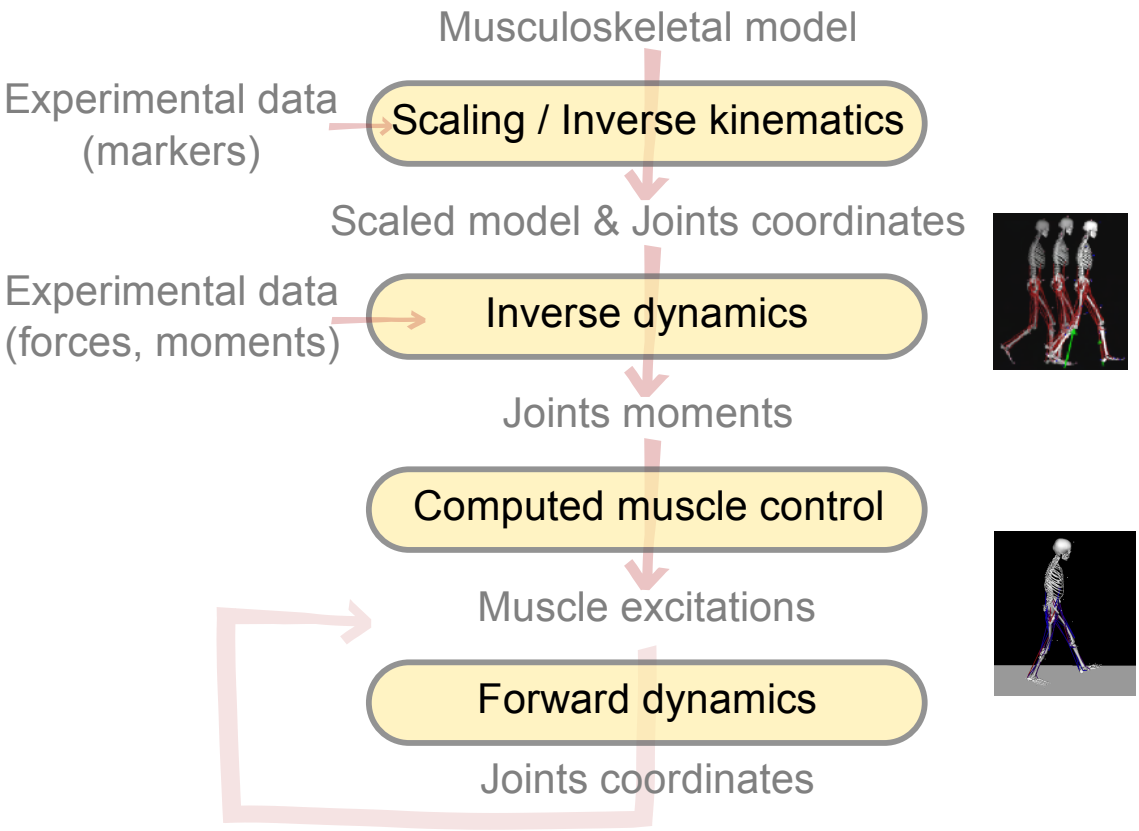


Figure 4.1: Global workflow in a biomechanical simulation using OpenSim

A short overview of the main workflow when creating a dynamic simulation of a recorded movement in OpenSim is necessary to follow the study. There are four basic steps as described in figure 4.1:
-First, a musculoskeletal model has to be scaled to the dimensions of the real subject. Each musculoskeletal model is made up of bodys (segments visualised as bones) that are attached to each other with specified functional joints. This forms the basic kinematic chain of your model that is needed for the first step. Motion capture markers are also specified. Each marker is attached

to a specific bone. After the scaling process, the inverse kinematics of the recorded motion is done. A file with all marker coordinates over time must be provided and OpenSim computes the joint coordinates that best reproduce the recorded motion. After the inverse kinematics, you will obtain a scaled model and all the joint coordinates vs. time characteristics. OpenSim's inverse kinematics is based on minimizing the root mean square error based on the distances between the real markers (when recorded) and the markers attached to the model. As you cannot attain a perfect model, there will always be an error but the goal is to minimize it.
-Second step is the Inverse Dynamics. Here, OpenSim uses experimental forces/moments and the joint coordinates from the first step to compute the joint moments vs. time characteristics of the recorded motion. Experimental forces and moments can come from a ground reaction forces plate for gait analysis or a simple force/torque sensor. To compute the inverse dynamics, OpenSim needs the masses and moment of inertia tensors of each segment of your musculoskeletal model. The dynamical resolution is based on Newton Euler equations and optimization algorithms (Residual Reduction Algorithm) for reducing dynamic inconsistencies. A ground contact model is included.
-Third step is intended to get the muscles excitations that produced the movement. The OpenSim model can have tendon-muscles attached between the bones which play the role of actuators. Based on the joint moments and the joint coordinates fron the first two steps, the Computed Muscle Control (CMC) algorithm generates a set of muscle excitations. OpenSim takes into account the dynamical behaviour and properties of tendons and muscles (that lead to the delay between the excitation and the reaction at the endpoint).
-Finally, a Forward Dynamics generates a muscle-driven movement simulation that matches the recorded movement.

OpenSim is complex software that has been developped over several years from highly advanced biomechanical laboratories and is now reaching maturity. The OpenSim community has now more than 50 developpers. The goal of this project is not to understand all the software and theory behind OpenSim. The paragraph above is only intended to provide a basic understanding of the functionnality. Further details, documents, tutorials and publications can be seen on the OpenSim and SimTK websites.

Concrete examples are provided and help understand the software's features. Examples of existing 'ready to use' models are shown in figure 4.2. They can be downloaded from the Library of Models SimTK project website (https://simtk.org/home/nmblmodels). Most of them were created by the NeuroMuscular Biomechanics Lab at Stanford University (http://nmbl.stanford.edu/).
OpenSim is used for biomechanics research, treatment planning, surgical simulation, computer animation and ergonomics. It enables a wide range of studies, for example analysis of walking dynamics, studies of sports preformance, simulation of surgical procedures, analysis of joints loads, design of medical devices and animation of animal movement. At the moment, three tutorials are included in the software. For instance, one tutorial investigates one of the most common walking abnormalities and helps to judge whether a patient's hamstrings are shorter than 'normal'. Another simulates the effects of a tendon transfer surgery on joint moment, moment arm and muscle force in the wrist.

By using OpenSim, our goal is to discover the differences between a 'human-like' biomechanical model of the foot and other simplified models. Different characteristics were described in the previous chapter, some of which are used in biomechanics and others are just very primitive representation. Is it possible to determine how foot design can be simplified? What do we lose in the process? How can we quantify the amount lost in terms of functionality? How important are the different foot joints found in the literature on human locomotion? How will a human adapt itself to a functional change? What are the characteristics of the foot joints (axis properties, stiffness)? Why are they like this?
A lower extremity model provided with OpenSim is the base model in our study. This model is called '3DGaitModel2392'. It is a 23 degrees of freedom model created by D.G. Thelen from the University of Wisconsin-Madison and Ajay Seth, Frank C. Anderson and Scott L. Delp from

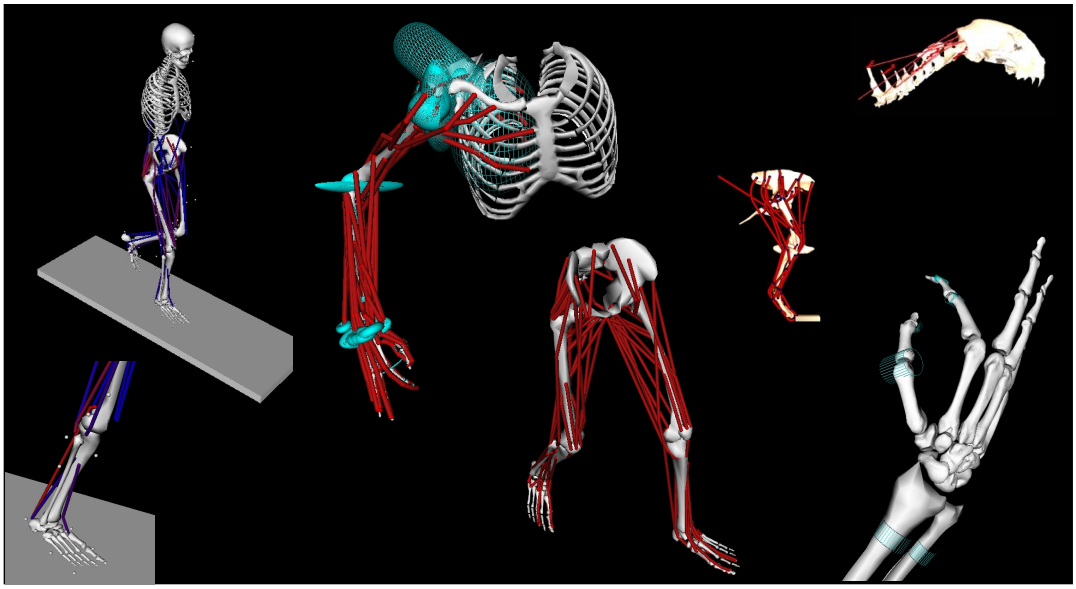


Figure 4.2: OpenSim examples of musculoskeletal models

Stanford University. The original model was modified and reduced to only a simple right foot and its lower leg. Firstly, our foot model consisted of only one ankle joint and five toe joints. As the project advanced, the model evolved and became more complicated.

4.3 First steps from Vicon to OpenSim

Preliminary tests were made to assess the feasability and the amount of work required for the biomechanical simulations. The complete workflow from motion capturing to simulation is described below.
The first step is the preparation of the model. OpenSim does not yet offer the possibility to easily create or change an existing musculoskeletal model in the graphical user interface (GUI). The only modifications available from the GUI are changes to muscles. If one wants to add or change degrees of freedom or change segment properties, the model file needs to be edited (.osim extension which has an XML structure) using a text editor. Through each step of the simulation, OpenSim accesses different XML files that must be carefully kept coherent and consistent at all times.
The next step is to prepare the markerset file that defines the marker positions on the attached segments (bodys). OpenSim uses this file as well as the musculoskeletal model file to complete the inverse kinematics from the recorded marker coordinates. A formal specification of the structure of an .osim model file and other OpenSim related XML files does not exist but support is available from the community. A detailed description of all input and output XML files required for each step is however available.
The following step involves gathering motion capture data. The objective is to export an OpenSim compatible file from the motion capture software. The motion capture system used for this project was provided by a company named Vicon, the market leader in motion capture products. Thus the hardware and software used here is used in gait laboratories as well as by most OpenSim users. The workflow in Vicon software can be described as follows: Initially a database is created that will hold the files, together with specifying a capture session. Once the system is calibrated, the foot attached markers are ready to be captured as the subject is moving. Then follows raw

data postprocessing: reconstructing the points from the cameras rays, automatically labeling each marker with the use of a skeleton, filling the gaps, filtering the trajectories, and finally exporting the files in the correct format (.trc) for use in OpenSim.

Figure 4.3 illustrates a simple motion of flexion/extension of the ankle and toes simulated using OpenSim. The plot shows the angles of the 7 joints evolving through time. Other simple foot movements were recorded and succesfully animated using OpenSim

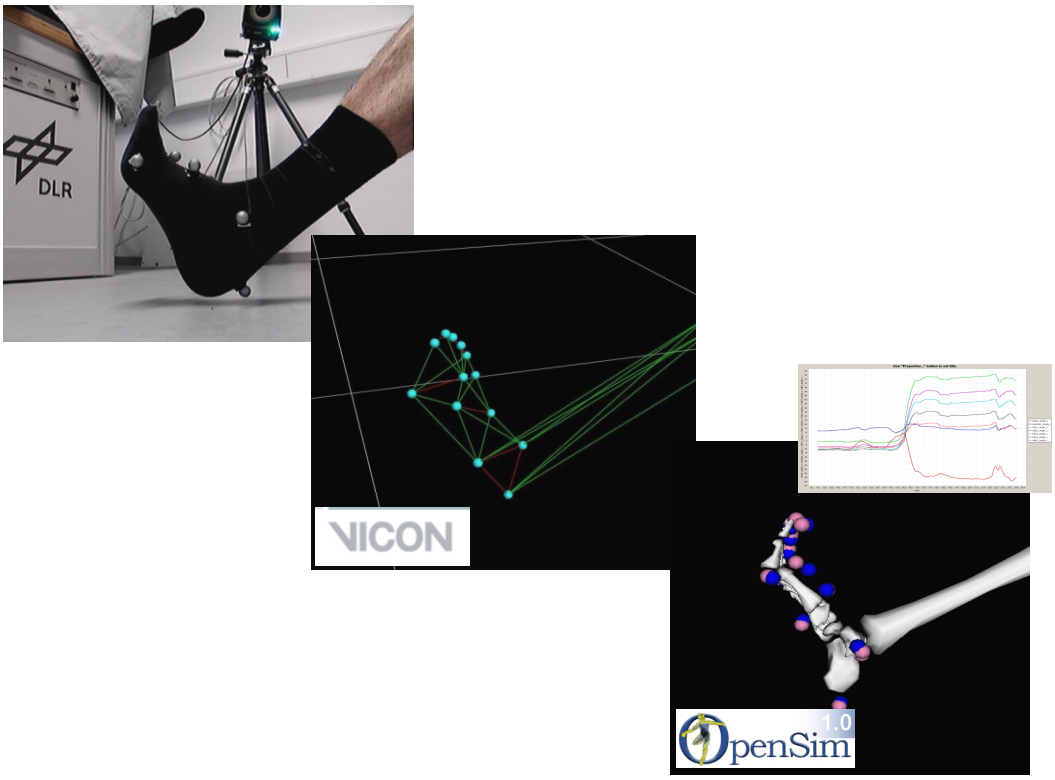


Figure 4.3: Preliminary test using biomechanical simulation software

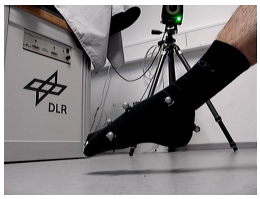
4.4 Motion analysis

The description of the Inverse Kinematics part of the main workflow of OpenSim has now been completed. This provides us with the coordinates of all the joints through time for a recorded motion. In order to obtain the joint moments during a gait cycle, the ground reaction forces and moments acting on the foot sole are required. These are generally measured with a ground reaction force plate which are most commonly used by gait analysis laboratories. Thanks to the generous help of Dr. Tusker (from the Technische Universität of Munich) and following several preparatory meetings, three days of measurements were organized with the gait analysis lab of the Faculty for Sport Science. The force plate used in the lab was made by the company Kisstler and provides us with 3 Forces, 3 Moments (one force and one moment in each plane) as well as the coordinates of the application point at a frequency of max 1000 Hz.
The pressure distribution on the foot sole is also of interest for this study. It is generally measured

using a foot pressure plate or pressure measurement insoles. Both systems only provide the user with normal pressure distribution acting on the sole (which is only related to the normal reaction force). Unfortunately, the only pressure insole system available in the gait laboratory was not calibrated and its heel cells were not working properly. The decision was taken not to use the collected data.

This project should not be restricted to normal walking, but also take into consideration others sorts of movement that humans do everyday. It is generally considered that for half the time, human locomotion is not straight. Turning and changing direction while walking have largely been neglected despite their obvious relevancy to functional mobility. Other special movements were studied in spite of the restrictions in the experimental setup. Trials of jogging, slow running, walking in circle, lateral stepping, jumping and object adaptation are presented in this study.

The OpenSim inverse kinematics process is based on the minimization of error between the model and the motion capture recording. For each frame, OpenSim computes the joint coordinates that will minimize the distance between each real marker and the corresponding model marker. The root mean square error (RMSE) is calculated and kept at a minimum in order to achieve this. This is necessary since a perfect musculoskeletal model does not exist. The resulting animated motion is thus only an approximation of reality. Figure 4.4 illustrates the calculation of the root mean square error value for one frame. The blue markers were recorded with motion capture while the pink markers are attached to the model.



$$root\ mean\ square\ error = \sqrt{\frac{1}{markers}\sum_{i=1}^{markers}\underbrace{\left(\vec{x}_i^{model} - \vec{x}_i^{real}\right)^2}_{\longleftrightarrow}}$$

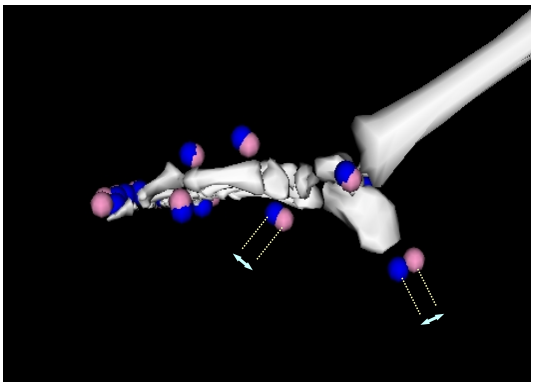


Figure 4.4: Root mean square error calculation illustration

The root mean square error is a measure of the 'human-like motion' accuracy of a given OpenSim model and therefore, it may be used as a criteria for the comparison of different models. Fourteen different models are compared here. Figure 4.5 & 4.6 illustrate the models that were used. These models were developed from the basic right foot model, in accordance with the research done in the third chapter. The models are:
-a very basic rigid model used as a reference for the maximum error,
-a model with one ankle allowing flexion/extension,
-a model with one midlefoot flexibility joint playing the role of the ankle,

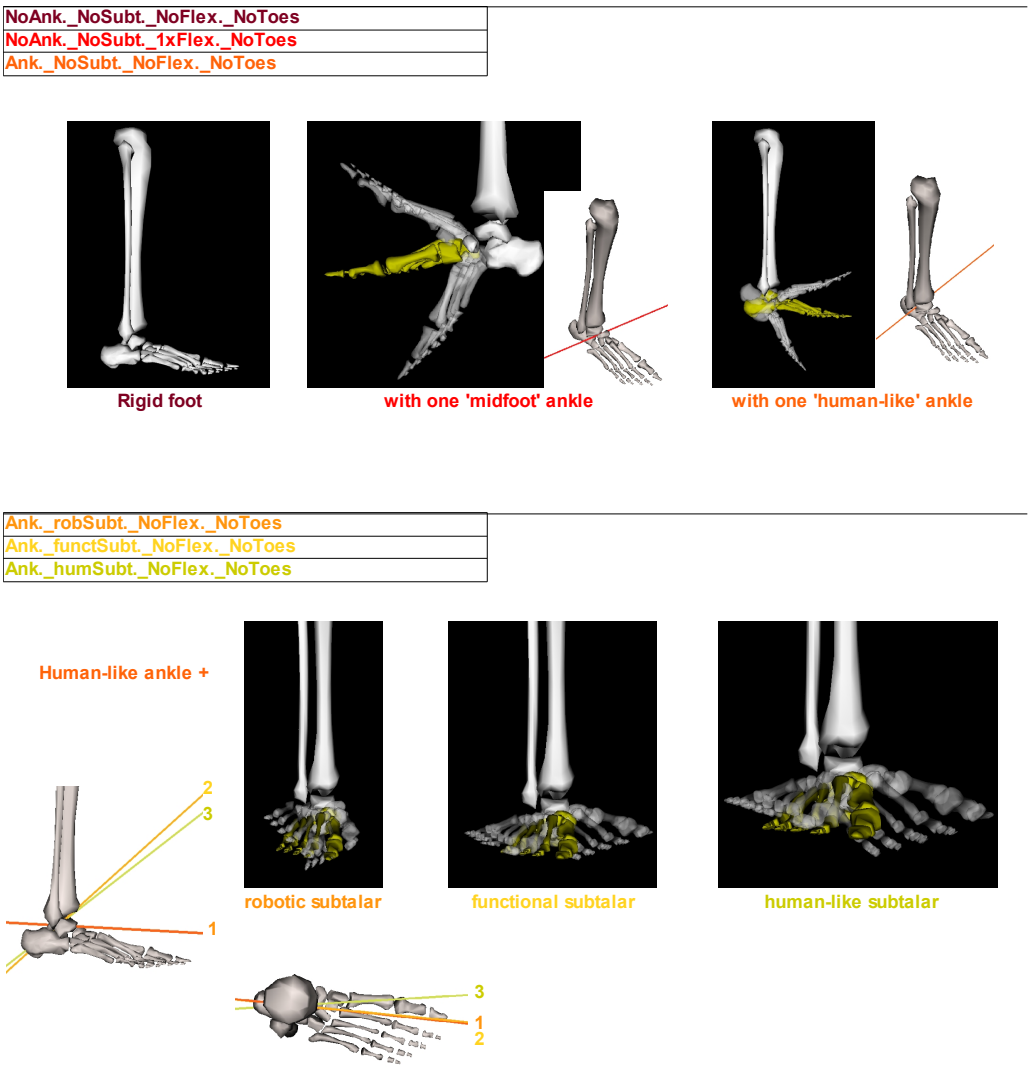


Figure 4.5: Biomechanical models used in experiments, ankle and subtalar models

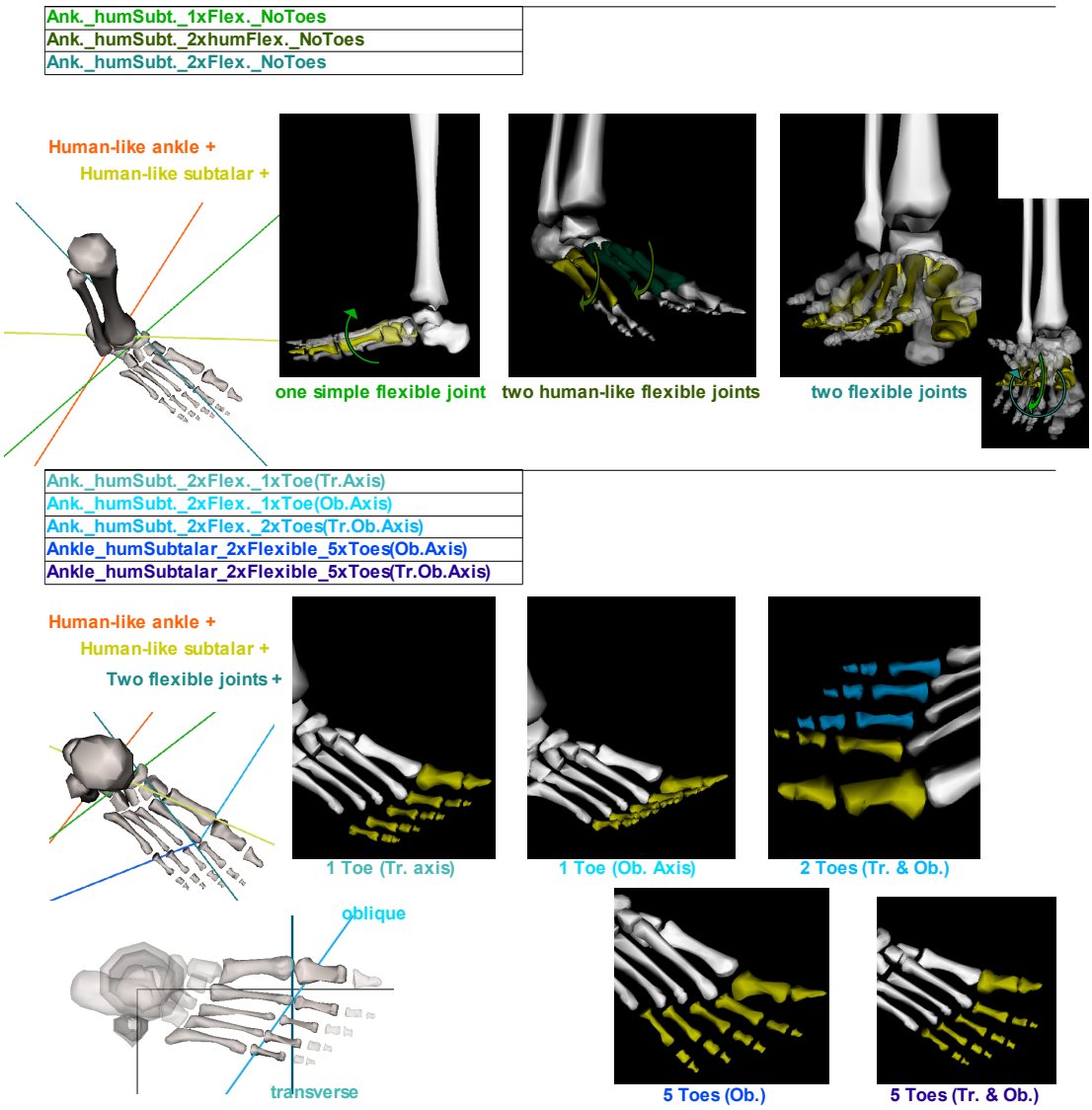


Figure 4.6: Biomechanical models used in experiments, flexibility and toes models

-a model with one ankle and one 'robot-like' subtalar joint,
-a model with one ankle and one 'functional' subtalar joint (45 from transverse plane),
-a model with one ankle and one 'human-like' subtalar joint (42 from transverse and 16 from sagittal planes),
-a model with one ankle, one 'human-like' subtalar joint and one simplistic flexibility joint in the sagittal body plane,
-a model with one ankle, one 'human-like' subtalar joint and two simplistic flexibility joints in the sagittal and frontal body plane,
-a model with one ankle, one 'human-like' subtalar joint and two 'human-like' flexibility joints in the sagittal plane representing the two longitudinal arches,
-same model plus a one toed 'transversal' axis MTP joint,
-same model plus a one toed 'oblique' MTP joint,
-same model plus a two toed human-like 'transversal and oblique' MTP joint,
-same model plus a two toed human-like 'oblique' MTP joint,
-same model plus a five toed human-like 'transversal and oblique' MTP joint,

Since a considerable amount of data results from these experiments, they were divided into three parts. The ankle and subtalar models are included in the first part, the flexible models in the second one and finally the toe models in the third. Figure 4.8 depicts the model comparison of the root mean square error vs. time characteristics for the first normal straight walking trial. Trial plots corresponding to the other types of movements are available in the appendix A and appendix B.

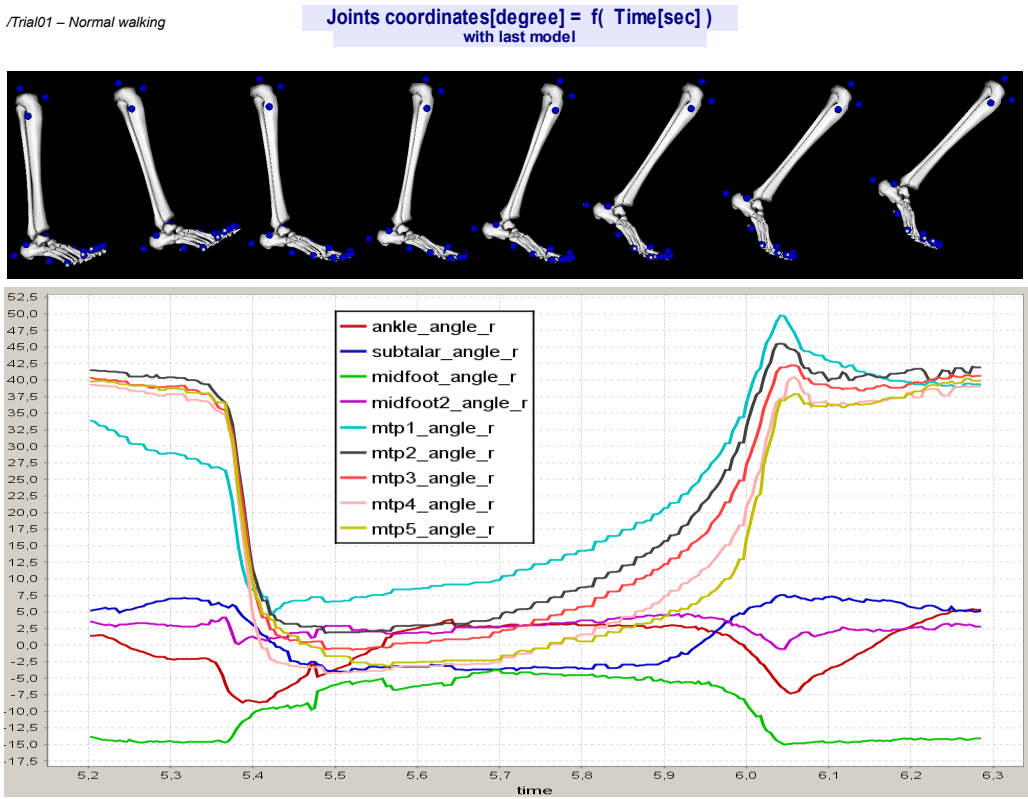


Figure 4.7: Joints coordinates through time on trial01 with last model

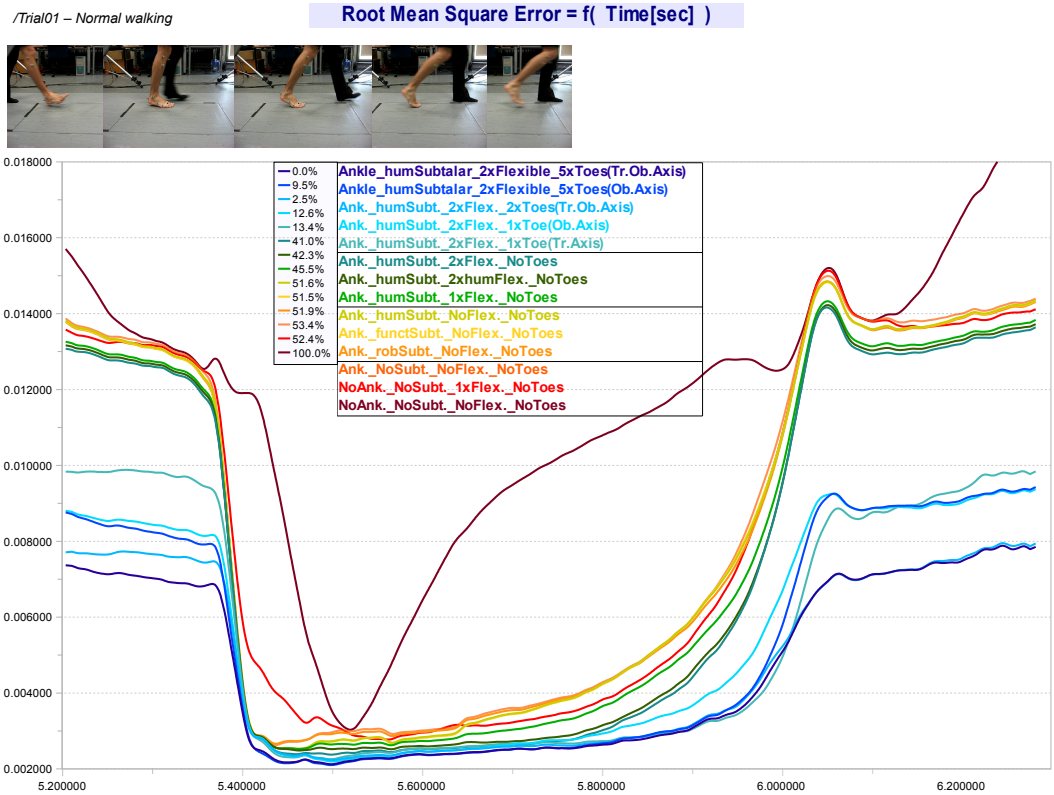


Figure 4.8: Root mean square errors during inverse kinematics of trial01 (normal walking) using different biomechanical models

The analysis of figure 4.8 reveals how the root mean square error decreases when the biomechanical model evolves. A perfect error would naturally be a zero error. In this trial, the upper curve is the one with the most errors and represents the rigid foot model. The lower blue curve with the least errors represents the model with an ankle, a subtalar joint, flexibility and five toes. As one can see on the chart, this model is far better than the rigid one.
These curves are used to quantify the differences emerging from an additional functional joint in the biomechanical model with respect to motion. Since the rigid foot is considered to be the worst design it is regarded as a referential upper limit of maximal RMS error. The last design is set to be the lower limit so that the total surface between the two curves is a 100% reference surface. For each other model, a comparison with the reference maximal error surface is made and a correspondance percentage is provided next to the model name and description for every trial.

This method was employed for the 31 trials. Figure 4.10 shows the average result for all trials. The model with only one ankle has an error surface that is 55.7% of that of the rigid model. Thus, the relative error in achieving a real-like motion decreases by 44.3 percents through the addition of an ankle joint to a rigid model. For a comparison between each trial or between different movements, please refer to the appendix B.

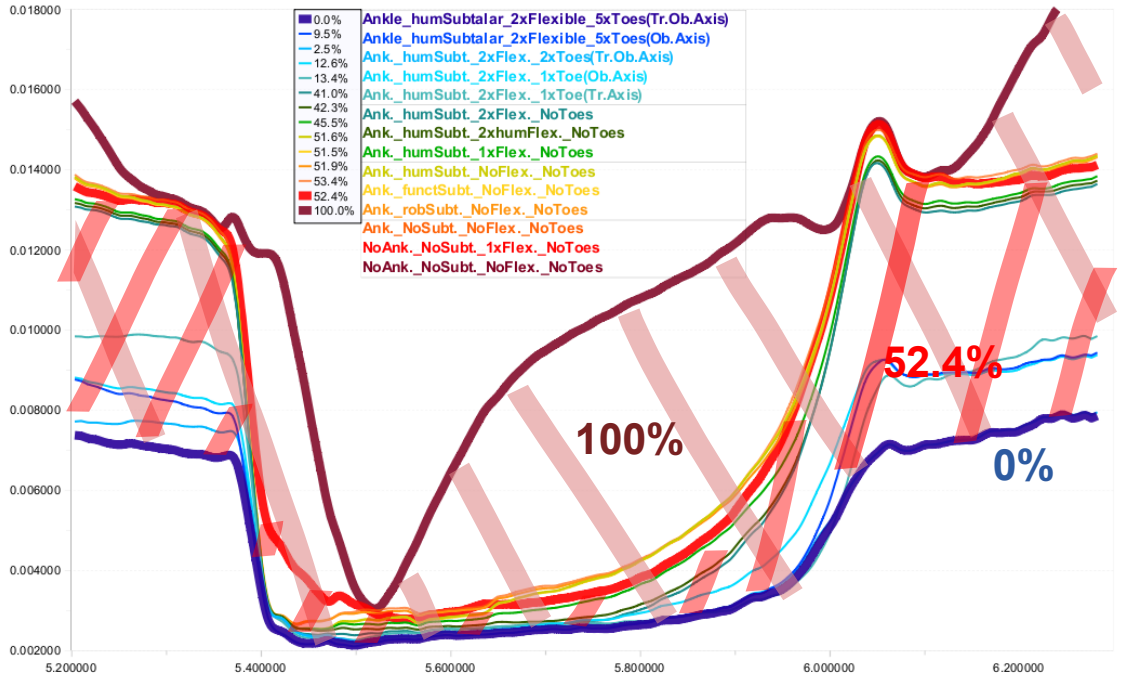


Figure 4.9: Example of error diminution comparison between one model and the reference models

	Model names and descriptions:	Total Error Surface %	Difference
Toes design	Ankle_humSubtalar_2xFlexible_5xToes(Tr.Ob.Axis)	0.0	-100.0
	Ankle_humSubtalar_2xFlexible_5xToes(Ob.Axis)	7.4	-92.6
	Ank._humSubt._2xFlex._2xToes(Tr.Ob.Axis)	2.9	-97.1
	Ank._humSubt._2xFlex._1xToe(Ob.Axis)	10.9	-89.1
	Ank._humSubt._2xFlex._1xToe(Tr.Axis)	11.8	-88.2
Flexibility design	Ank._humSubt._2xFlex._NoToes	36.9	-63.1
	Ank._humSubt._2xhumFlex._NoToes	39.6	-60.4
	Ank._humSubt._1xFlex._NoToes	42.0	-58.0
Subtalar design	Ank._humSubt._NoFlex._NoToes	47.5	-52.5
	Ank._functSubt._NoFlex._NoToes	48.4	-51.6
	Ank._robSubt._NoFlex._NoToes	54.2	-45.8
Ankle design	Ank._NoSubt._NoFlex._NoToes	55.7	-44.3
	NoAnk._NoSubt._1xFlex._NoToes	56.6	-43.4
	NoAnk._NoSubt._NoFlex._NoToes	100	

Figure 4.10: Total results of the root mean square error comparison between 14 models during 31 trials

4.5 First Results

4.5.1 Ankle and subtalar models

The analysis of the experimental results gives a good notion of the role and importance of the ankle. The global percentage of the error surface for the model with an ankle is 55.7% of that of the rigid model. When looking at other movements such as jumping, the reduction of the error relative to the rigid model is higher and achieved nearly 70%. It is thus clear that the role of the ankle in the global motion of the foot is very important. This is now widespread knowledge and

the ankle is the first thing to be implemented in the design of a robot foot and is usually present in every bipedal robot.
However, if the ankle extension/flexion functionality is displaced and moved to a 'non human-like' midfoot joint as for the rifkin's artificial foot presented in chapter 3, the results are very interesting. The error surface of this model (red model) is 56.6% of that the rigid model. The difference between a human-like ankle foot and a midfoot ankle foot can be neglected if we choose to look only at the motional aspect.

	Model names and descriptions:	Total Error Surface %	Difference	Walking		Running		Turning left		Turning right		Lat. Steps		Jumping		On the toes		Adaptation	
Ankle design	Ank._NoSubt._NoFlex._NoToes	55.7	-44.3	61.5	-38.5	48.3	-51.7	71.7	-28.3	71.7	-28.3	59.5	-40.5	22.8	-77.2	27.1	-72.9	54.6	-45.4
	NoAnk._NoSubt._1xFlex._NoToes	56.6	-43.4	59.5	-40.5	50.4	-49.6	72.2	-27.8	65.6	-34.4	58.7	-41.3	27.1	-72.9	31.1	-68.9	62.5	-37.5
Rigid model (Ref.)	NoAnk._NoSubt._NoFlex._NoToes	100	0.0	100	0.0	100	0.0	100	0.0	100	0.0	100	0.0	100	0.0	100	0.0	100	0.0

Figure 4.11: Total result for the ankle designs

Adding a subtalar joint to the ankle model also decreases the error surface. Three different models were tested using OpenSim's inverse kinematics and the analysis of the root mean square error. The first model corresponds to the 'robot-like' subtalar design described in chapter 3, where the axis passes through the foot plane. The model is able to twist its feet as a result, with this ankle axis (named 'robSubt'). The second model ('humSubt') is inspired by the human-like subtalar joint as defined by biomechanicians, with the oblique axis permitting a motion in the three cardinal planes. The third ('functSubt') is a 'functional' variation of this design with a semi oblique simplified axis which permits a motion in only two planes.
If the three subtalar models are compared to the ankle model (as a reference), the average decline in the error surface percentage is 8.2 points (for the human-like subtalar). The robotic subtalar only decreases the error percentage by 1.5 points and thus is the least accurate for human-like motion. The simplified functional subtalar joint decreases the error by 7.3 points. This value is satisfying if we consider the advantage of a simplified axis design.
As expected, the average drop in error percentage for the 'turning' trials is considerable in comparison to the straight walking movements. The average human subtalar model drop in error percentage for the 'turning right' trials is 18.5 points and only 3.2 for the 'straight walking' trials. This confirms the importance of the subtalar joint in movements other than normal straight walking. Actually, all movements that are not restricted to the sagittal body plane involve the subtalar joint. Thus, neglecting the subtalar joint in the design of robot feet may lead to problems as a robot would probably not exclusively walk straight. For movements such as jumping forward or running on a flat surface, the subtalar joint is of little importance.

	Model names and descriptions:	Total Error Surface %	Difference	Walking		Running		Turning left		Turning right		Lat. Steps		Jumping		On the toes		Adaptation	
Subtalar design	Ank._humSubt._NoFlex._NoToes	47.5	-8.2	58.3	-3.2	45.5	-2.8	61.0	-10.8	53.2	-18.5	46.7	-12.8	20.3	-2.5	23.0	-4.1	47.8	-6.8
	Ank._functSubt._NoFlex._NoToes	48.4	-7.3	58.2	-3.3	45.7	-2.6	62.5	-9.2	55.4	-16.3	48.4	-11.1	20.5	-2.3	23.4	-3.7	48.3	-6.3
	Ank._robSubt._NoFlex._NoToes	54.2	-1.5	64.6	3.1	47.3	-0.9	66.9	-4.8	49.2	-22.5	76.4	17.0	23.5	0.7	28.0	0.8	51.6	-3.0
Ankle model (Ref.)	Ank._NoSubt._NoFlex._NoToes	55.7	0.0	61.5	0.0	48.3	0.0	71.7	0.0	71.7	0.0	59.5	0.0	22.8	0.0	27.1	0.0	54.6	0.0

Figure 4.12: Total and partial results for the subtalar designs

4.5.2 Flexible models

Three models are used to understand the flexibility of the foot. Flexibility is here achieved with simple joints located in the midfoot. The first model ('1xFlex') has only one joint which permits a extension/flexion motion of the frontfoot in the sagittal plane (creating a very simple arch). The second model ('2xhumFlex') has two separate joints representing the two longitudinal arches described in chapter 3. The third model ('2xFlex') incorporates the joint of the first model as well as an additional midfoot joint which allows motion in the transverse plane, thus permitting rotation of the frontfoot.
The first, second and third models yield a drop in average error surface by respectively 5.5%, 8.0% and 10.6%. By comparing the first and third design, it can be inferred that the rotational flexibility motion is as important as the flexibility in the sagittal plane. In the turning trials, the rotational flexibility even plays a more important role and is responsible for approximately 10% of the error drop.
The second model does not fare as well as the third one, despite the fact that biomechanicians often describe the foot as a two longitudinal arch system.

	Model names and descriptions:	Total Error Surface %	Difference	Walking		Running		Turning left		Turning right		Lat. Steps		Jumping		On the toes		Adaptation	
Flexibility design	Ank._humSubt._2xFlex._NoToes	36.9	-10.6	46.8	-11.5	37.8	-7.7	42.7	-18.3	38.3	-14.9	36.2	-10.5	15.6	-4.7	17.5	-5.6	41.1	-6.7
	Ank._humSubt._2xhumFlex._NoToes	39.6	-8.0	47.7	-10.6	39.2	-6.3	48.0	-13.0	42.4	-10.8	39.9	-6.8	15.9	-4.4	18.1	-4.9	44.0	-3.8
	Ank._humSubt._1xFlex._NoToes	42.0	-5.5	50.7	-7.6	41.2	-4.3	54.3	-6.7	44.6	-8.6	42.5	-4.2	17.1	-3.2	19.5	-3.5	43.7	-4.1
Ankle Subt. (Ref.)	Ank._humSubt._NoFlex._NoToes	47.5	0.0	58.3	0.0	45.5	0.0	61.0	0.0	53.2	0.0	46.7	0.0	20.3	0.0	23.0	0.0	47.8	0.0

Figure 4.13: Total and partial results for the flexible designs

4.5.3 Toes models

Five models are used in order to study the motion of the toe (MTP) joints. The first two models (labeled '1xToe') have only one simple toe joint (the first one with a transverse axis 'Tr.Axis' and the second one with an oblique axis 'Ob.Axis'). The third model ('2xToes') has two toe joints regrouping the first two human toes and the last three. The axis position and orientation of the two joints were inspired by literature (chapter 3). The first axis (inner joint) is in the transverse plane and the second axis is oblique (lateral joint). The last two models have five separate toe joints. While in the fourth model all five toe joints have an oblique axis, in the fifth model the first two toe joints have a transverse axis.
The end results for all trials show a spread in error percentage drop between 25.1 and 36.9 points. The five toed transverse and oblique axis design is the most accurate model while the one toed transverse axis design has the worst results. The global difference between a transverse and oblique axis in a one toed design is fairly insignificant (+1.0 % for oblique axis). However, even if the transverse axis has proven more precise for motion in the sagittal plane such as walking or running, it is also apparent that the oblique axis is very accurate in other motion where the lateral toes are used more, such as turning right or lateral steps. For these movements, the oblique one toed joint obtains considerably better results when compared to the transverse axis design (+10%).
The third design combines the advantage of the two transverse and oblique axis so that the mean error percentage drop is significantly higher than for the one toe design in all trials. The average value for the two toes design (-34.0%) is also substantially better than the five separate toes design with only one oblique axis (-29.5%). Considering the results of the fifth design, it furthermore becomes clear that five toes provide only a marginal advantage over a two toe design (only a 2.9 points difference).

	Model names and descriptions:	Total Error Surface %	Difference	Walking		Running		Turning left		Turning right		Lat. Steps		Jumping		On the toes		Adaptation	
Toes design	Ankle_humSubtalar_2xFlexible_5xToes(Tr.Ob.Axis)	0.0	-36.9	0	-46.8	0	-37.8	0	-42.7	0	-38.3	0	-36.2	0	-15.6	0	-17.5	0	-41.1
	Ankle_humSubtalar_2xFlexible_5xToes(Ob.Axis)	7.4	-29.5	10.3	-36.5	9.5	-28.2	10.2	-32.5	8.1	-30.2	6.6	-29.5	2.6	-12.9	2.1	-15.4	4.3	-36.8
	Ank._humSubt._2xFlex._2xToes(Tr.Ob.Axis)	2.9	-34.0	2.0	-44.8	0.6	-37.2	2.6	-40.1	1.7	-36.6	5.6	-30.6	1.0	-14.6	2.2	-15.3	7.2	-33.9
	Ank._humSubt._2xFlex._1xToe(Ob.Axis)	10.9	-26.1	13.3	-33.5	11.0	-26.8	15.5	-27.2	8.8	-29.5	10.6	-25.6	4.0	-11.5	5.0	-12.5	12.8	-28.3
	Ank._humSubt._2xFlex._1xToe(Tr.Axis)	11.8	-25.1	12.6	-34.2	9.0	-28.7	9.3	-33.4	14.3	-24.0	20.3	-15.9	3.3	-12.3	5.2	-12.2	13.9	-27.2
Reference	Ank._humSubt._2xFlex._NoToes	36.9	0.0	46.8	0.0	37.8	0.0	42.7	0.0	38.3	0.0	36.2	0.0	15.6	0.0	17.5	0.0	41.1	0.0

Figure 4.14: Total and partial results for the toes designs

4.6 Summary Conclusion

The biomechanical comparison performed in this chapter gives a good insight into the extensive possibilities of biomechanical software. Several models were simulated during different human foot motions and an evaluation of the human-like accuracy of each model was given. Even if the method used depends to a large extent on the distribution of the motion capture markers, the results have nevertheless to be taken into consideration when designing an artificial foot since the motional aspect is very important for the final product.
The biomechanical simulations reveal that the human foot characterisitics and joint motions depend greatly on the particular movement that the subject is performing. Since we can assume that the robot will not only be walking straight, this therefore implies that special functional units such as the subtalar joint and rotational flexibility must also be taken into account.
OpenSim has shown its utility in the field of robotics as it provides an easy-to-use, open-source, very complete tool to perform biomechanical studies. However, the study was restricted because of the impossibility to perform automated simulations and run self programmable scripts. We expect a lot more with the next release of OpenSim 2.0 as the sources and a public API will be available. This will permit for example to call OpenSim from Matlab in order to automaticaly compute an optimal foot design.

Chapter 5

Function analysis of the foot

5.1 Introduction

It is important to focus the study on the different functions of the foot. In the previous chapter, particular attention was given to how perfect human-like foot motion could be recreated. Nevertheless, the biomechanical simulations here highlighted the fact that it is also necessary to focus the project on the different functions of the foot and not only on how we can recreate the perfect human-like foot motion.
Obviously, it is important to know how we can recreate mechanically the perfect human-like motion of the whole foot structure. It is still important to know how many degrees of freedom we need in order to achieve accurate motion in the ankle for example. It is interesting to answer the question of the joint axis positions if we assume that the foot has simple uniaxial mechanical joints. What motion are we loosing if we assume that the ankle and the subtalar joints are a universal cardan joint? All these questions have to be considered in order to undestand how simply the artificial foot can be designed.
However, the main objective is to obtain an artificial foot that can recreate efficiently and as simply as possible, the main functionalities of the foot, and not only the motion. Once the basic functions and how they are solved in the human foot are known, we might then use another technical solution to achieve the same function. The next logical step is to undertake a study of the functional properties of a foot by using our understanding acquired within the past chapters. It was decided to take inspiration from a design method that has proven shown its utility in innovative engineering, namely: the Function Analysis.
The Function Analysis is a creativity technique that helps the designer or engineer define the problem that needs to be solved, and clarify the real questions. It helps to recollect special innovative solutions by widening the searchfield and by fighting mental inertia. It is a method used in many engineering fields such as aerospace, where engineers have to deal with very complex problems.
The following chapter presents our application of the function analysis method to the human foot. Firstly, the biological function will be abstracted starting from the human foot. Then, the Function Analysis method, its benefits and objectives will be presented. Finally, the artificial foot will be discussed with respect to the strict defined plan of a functional analysis.

5.2 Functions of the human foot/Bottom-up process

The approach described in this section is a so called bottom-up process. The third chapter presented the anatomical and functional morphology of the biological system. The fourth chapter analysed its biomechanics. From this previous understanding of the foot we may now abstract the principles in order to define the basic functions that an artificial foot should fulfill. Starting from the human foot, the principal characteristics may be presented as follows.

The ankle basic function is to allow controlled motion of the foot in the sagittal plane.
This function has different purposes, constraints :
-The sole of the foot is correctly presented (regarding the sagittal plane) to the ground before contact. Independantly of whether the heel (walking) or the frontfoot (jogging) has to be presented and no matter what the slope of the surface.
-It permits rotation of the leg when the body advances in the single support phase. So that the weight support is optimal and the foot does not slip even on a sloping surface (all the foot sole in contact with ground).
-The ankle is actuated for stabilisation (for example when standing) and for propulsion (final part of stance phase) when the foot acts like a lever and the Triceps Surae gives most of the force to propuls the body upward and forward.
-The ankle absorbs shocks, vibration (energy) when landing on keel (walking) or on the toes (running). Then, it returns this energy back. Therefore, the antagonist ankle muscles are important through their elasticity because they control the ankle stiffness.
-The ankle ligaments give passive elasticity to the ankle. The flexibility of the joint in the other two planes is important when the joint is under stress. They resist to the motion in the other two planes but permit limited motion when very high forces are applied so that the ankle is not deteriorated.
-The ankle facilitates foot clearance during the swing phase (ankle dorsiflexion).

The subtalar complex permits a controlled triplanar motion of the foot with a planal dominance in the transverse and frontal planes. These function goals are not yet fully understood but some features are discussed here:
-It permits the sole of the foot to be optimally presented to the ground before contact (regarding other planes). No matter how the leg is orientated and for surfaces with slopes other than in the sagittal plane (no matter which way the human is walking). Foot sole is presented to maximize the grip and the lever arm during support.
-It absorbs internal and external rotation of the leg. Allowing the rotation of the leg on single support phase (for turning hip on balanced gait or when turning for example) but limiting this rotation by acting like a mitered joint, which is a hinge at 45 $^{\circ}$ that acts as a torque converter.
-It helps allowing the motion of the knee while the foot and the hip are fixed, like the
-It permits the shift from the medial 'soft' arch (beginning of stance phase) to the lateral 'rigid' arch (at the end of stance phase). It unlocks (with supination) and locks (with pronation) the midtarsal joint motion. Both permit the transition from the shock absorber function to the rigid lever function during stance phase.

The midfoot allows a controlled adaptation of the midfoot:
-It adapts to uneven ground, obstacles under the foot plant so that the foot sole has a maximum contact area distribution.
-It absorbs shocks and vibrations on the first part of stance phase and stored the energy through a flexible foot arch.
-It is able to create a propulsive rigid lever for transmitting energy from ankle muscles to the ground and returns stored energy in the last part of stance phase.
-It permits the twist of the frontfoot. Thus, it allows limited internal and external rotation of the leg through the subtalar joint and keep the frontfoot sole in contact with the ground.

The MTP joints permit the controlled flexion/extension of the toes:
-to adapt to uneven ground with obstacles (maximum contact surface).
-They act as a second ankle for the end of the stance phase, when lever is active and give propulsive forces.
-When flexed, they straighten the plantar fascia (windlass effect) and rigidify the whole foot arch.
-Toes clearance during the swing phase (dorsiflexion).

The foot plant manages the direct contact with ground:
-It absorbs shocks and vibrations with the soft tissue, fatpad under heel and plantar pads under ball of the foot. It protects from ground agression like a cushion.
-It improves adherence with ground to not slip when supporting the weight.
-It rolls over the ground during each walking step, roughly analogous to a wheel
-It provides sensory feedback: (pressure, heat).

5.3 The Function Analysis method

Various methods are used in the field of engineering and design to facilitate creativity when solving a problem. These techniques are not algorithms but methods that appear to be helpful when dealing with non structured problems. The most well known technique is probably Brainstorming. However more complex methods have been developped such as Value Engineering. In this project, a function-based analysis is used such as one utilised in the initial stage of a value analysis. This process is intended to define, classify and evaluate functions that the product must fulfill. It tries to determine which functions or performance characteristics are important. This method would correspond to a top-down approach as it tries not to start from the human foot but directly from the function that the product must fulfill. It is therefore opposite to the bottom-up approach described in the previous section. However, we think that both combined approaches will lead not to bypass crucial characteristics of an artificial foot. Several scientists insist on integrating function-based design on concept generation whether it is for biomimetics or for robotics. Applying functional modeling to biologically inspired design offers more complete, more systematic modeling that reveals additional aspects.

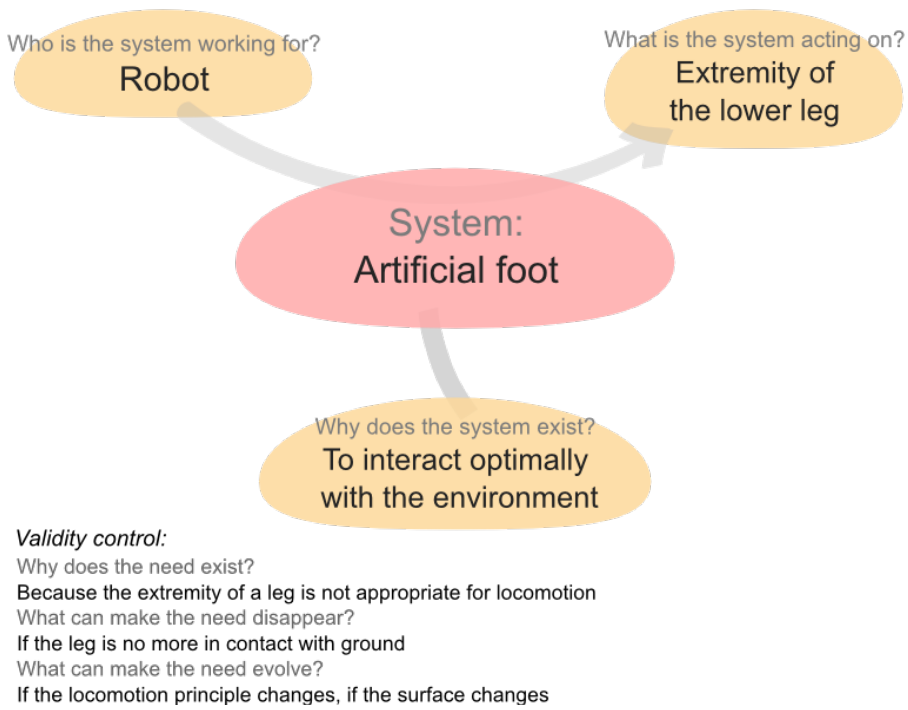


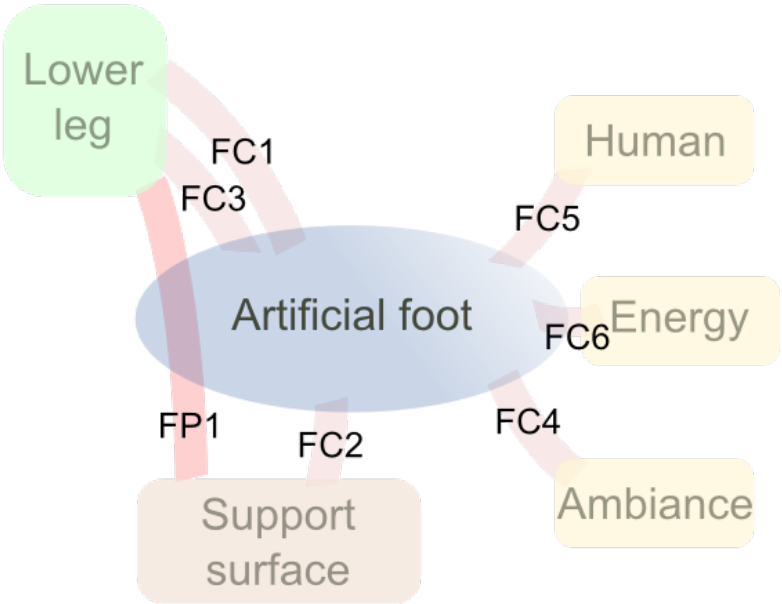
Figure 5.1: Definition of the fundamental 'need' for an artificial foot

5.3.1 'Need' analysis

The first step of the function-based analysis is to determine the purpose for which a product, or service exists. This helps to (re)define the so-called fundamental 'need' of the product. This function is also called the task of the product.
Starting from the product, the global system in which the product is acting is firstly specified. The product can be the whole system or just a part of it. It is everything that is under the control of the designer. Then, the 'need' is (re)invented by answering these three questions: Who is the system working for? On what is the system acting? Why does the system exist? The 'need' analysis is then presented in a schematic diagram.
In this project, the final product is an artificial foot and is defined as the system. The artificial foot is working for the robot. It is acting on the lower extremity of the leg. It exists to interact optimally with the environment.
In order to validate the need, three other questions have to be answered: Why does the need exist? What can make this need disappear? What can make this need evolve? The need exists because the extremity of a leg is not appropriate for bipedal locomotion. The need will disappear if the legs are no more in contact with the ground, for example if the robot does not walk with legs anymore. The need will evolve if the walking surface changes, if the locomotion principle changes

5.3.2 Environment diagram

The environment diagram is the next step in the function analysis. This diagram is here done for the normal use of the product, this means when the robot is using its feet for locomotion. The environment elements are firstly listed and integrated into the diagram. We have here 4 global environment elements that are in 'contact' with the product during a locomotion:
-the lower leg (its extremity),
-the support surface (ground),
-the ambiance, everything around the foot except the ground (air, obstacles in the way of the foot, liquid),
-the human who controls the robot.
-the energy.
Then the functions are carefully formulated. Distinction is made between principal functions FP and constraint functions FC. The environment diagram is shown in figure 5.2.



Functions:
FP1: The artificial foot must permit the extremity of the lower leg to support on every ground with an optimal contact during all support phase for every movement
FC1: ... stabilize and propulse the leg when needed
FC2: ... absorb shocks and vibrations on impact with ground
FC3: ... facilitate the shift of the leg when not weightbearing
FC4: ... resist to environmental aggressions
FC5: ... please the human
FC6: ... minimize energy consumption

Figure 5.2: Environment diagram of the function analysis for the artificial foot

Conclusion

The 6 months project work that was done in the bionics group was globally successful in understanding the role of the foot during human locomotion. Initially, it allowed us to gain knowledge in biomechanical simulations of movements and motion capturing. Then to developp a strategy for defining the work and experiments necessary to fullfill the main objective.

Throughout this project, a global persepective on the human foot was given considering the main objective of designing an artificial foot. In the third chapter, we were able to give a basic understanding of how the human foot works. This was done by looking at anatomical aspects of the foot. Other important informations were taken from other fields specialized in the foot. Informations on the functional physiology were crucial for the comprehension of the role of the foot in locomotion. An insight in the design of artificial foot was finally made by looking at current robotic and prosthetic researches.
Accordingly to the different characteristics found in the third chapter, a method was then described in the fourth chapter to compare different models, designs. Using a motion capture system and biomechanical software, foot motions during various activities of a subject were recorded and analyzed. A comparison between fourteen designs was performed for these trials.
Consequently to the research that was made for understanding the human foot, a biologically inspired approach revealed the principles and functions that an artificial foot will have to implement. Therefore, the commonly used Function Analysis method was presented and applied to the human foot in the fifth chapter, leading to the formulation of seven functions.

As a relative newcomer to the field of robotics, I was very happy with the knowledge and experience I was able to gain during my stay in the institute.
I would like again to extend my warm thanks to everyone that helped me during my research project and in particular the bionics team.

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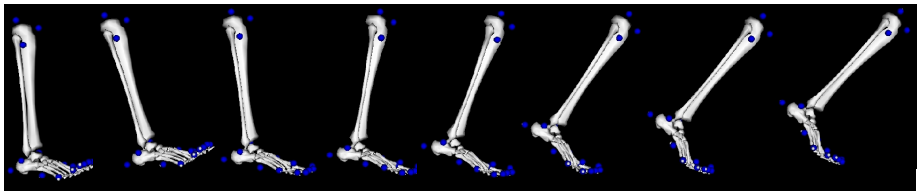
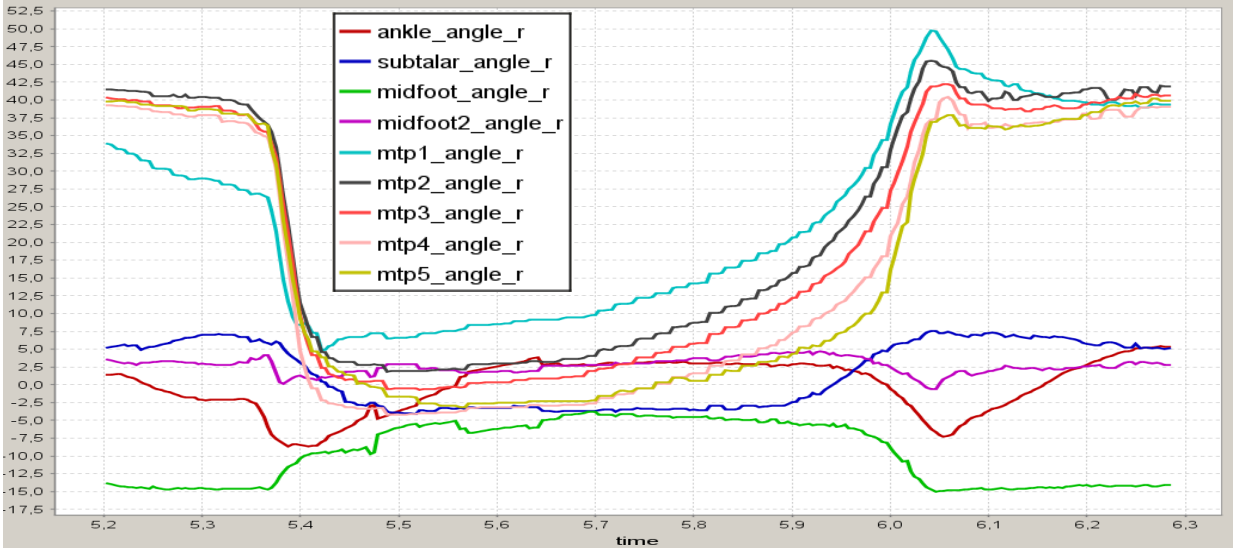
List of Figures

Appendix A

Inverse kinematics results

trial01





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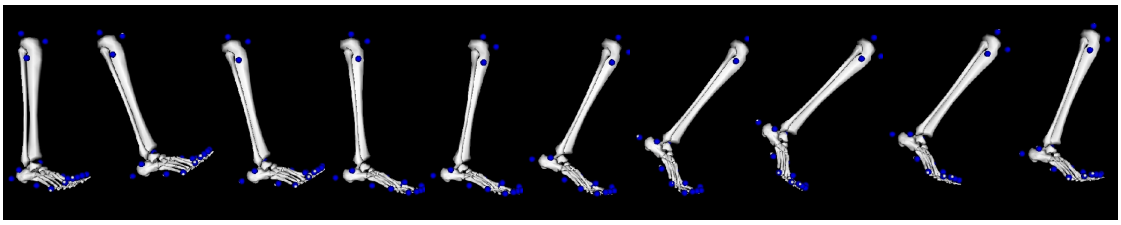

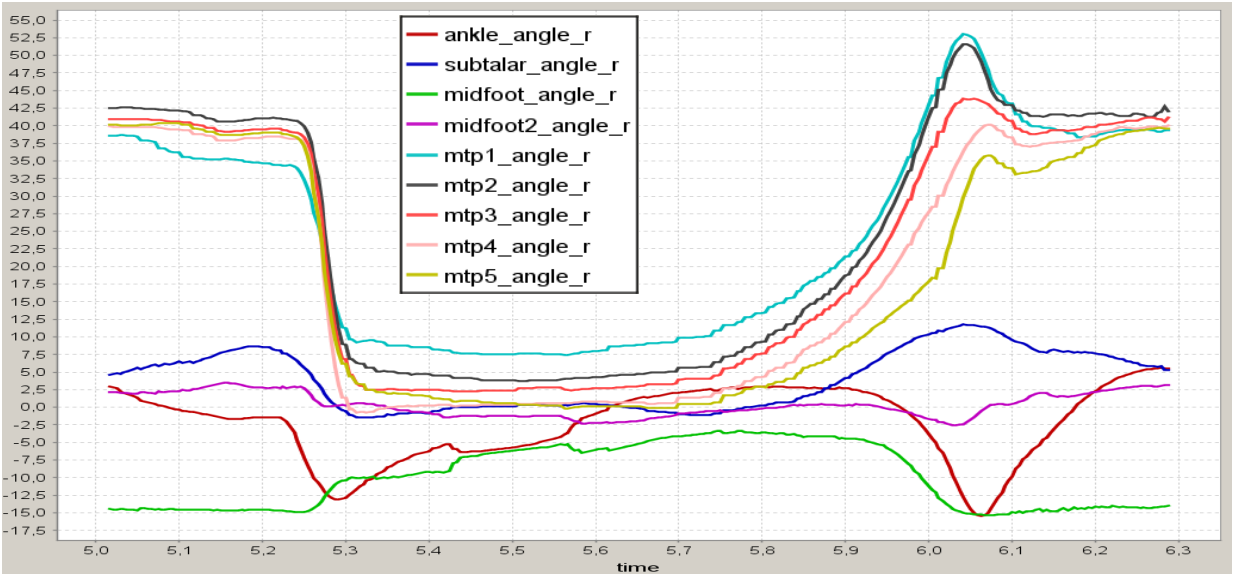

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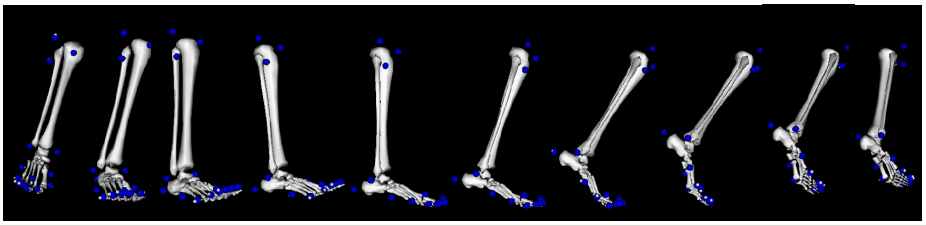

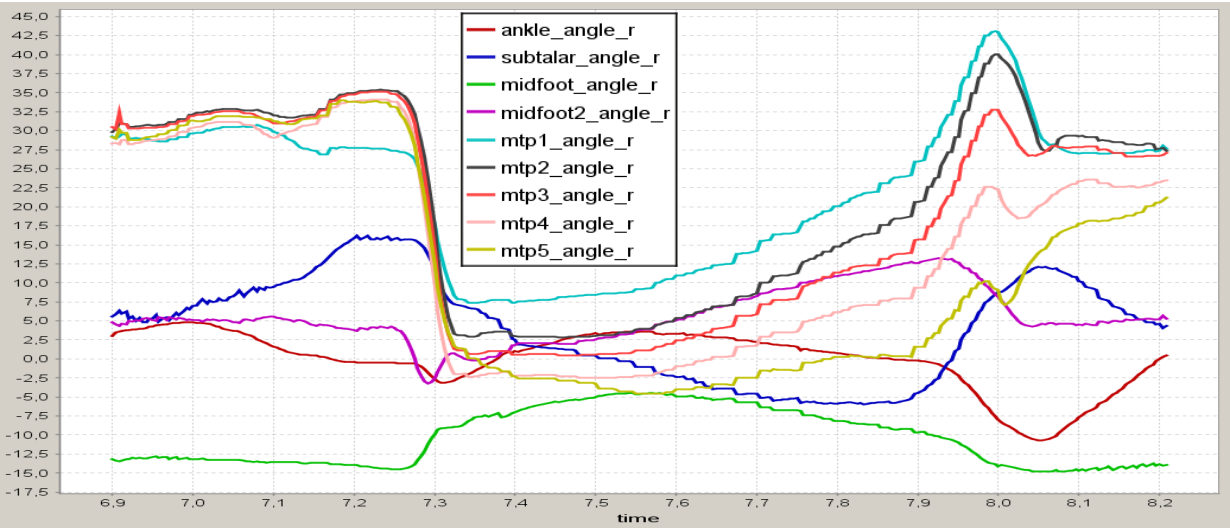

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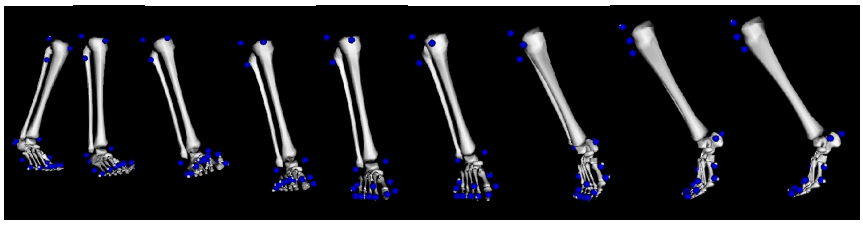

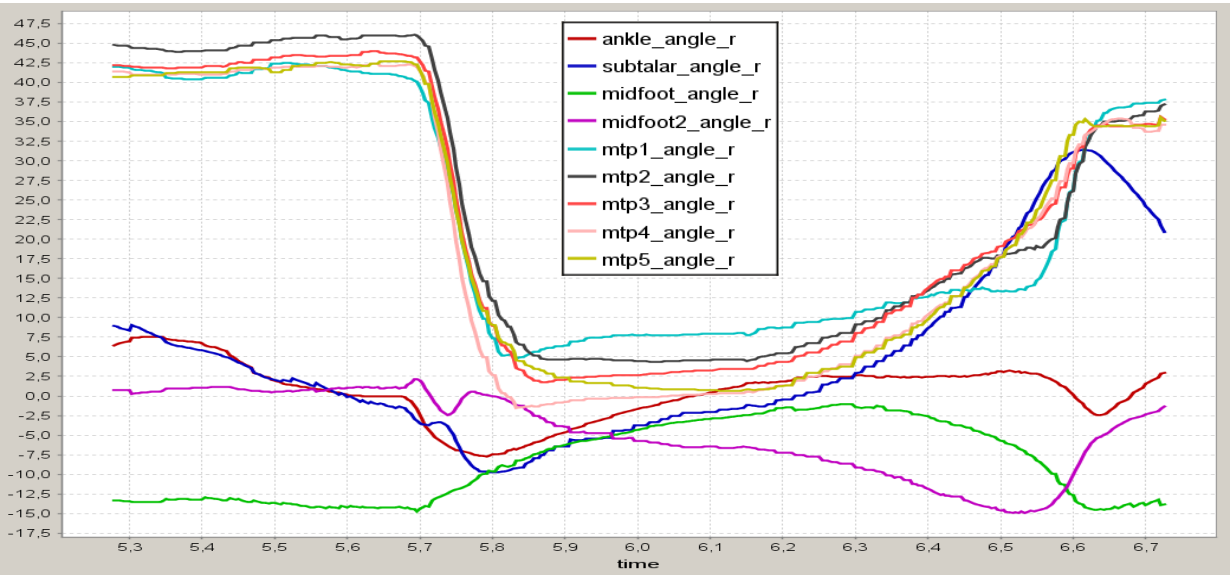

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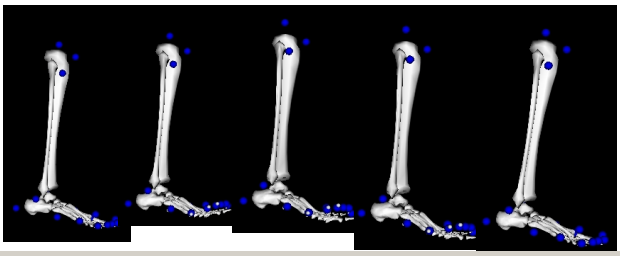

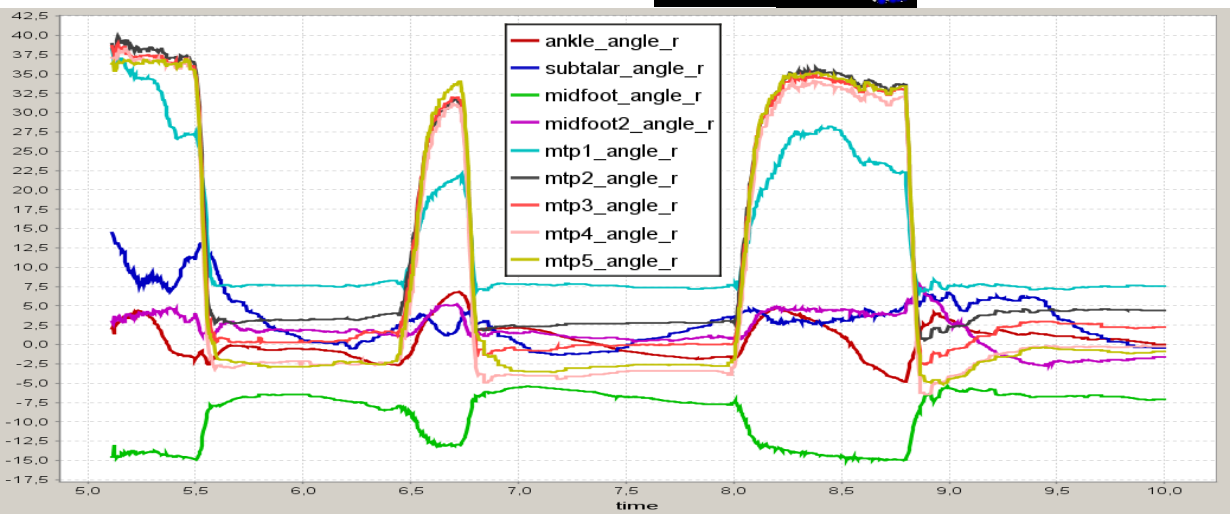

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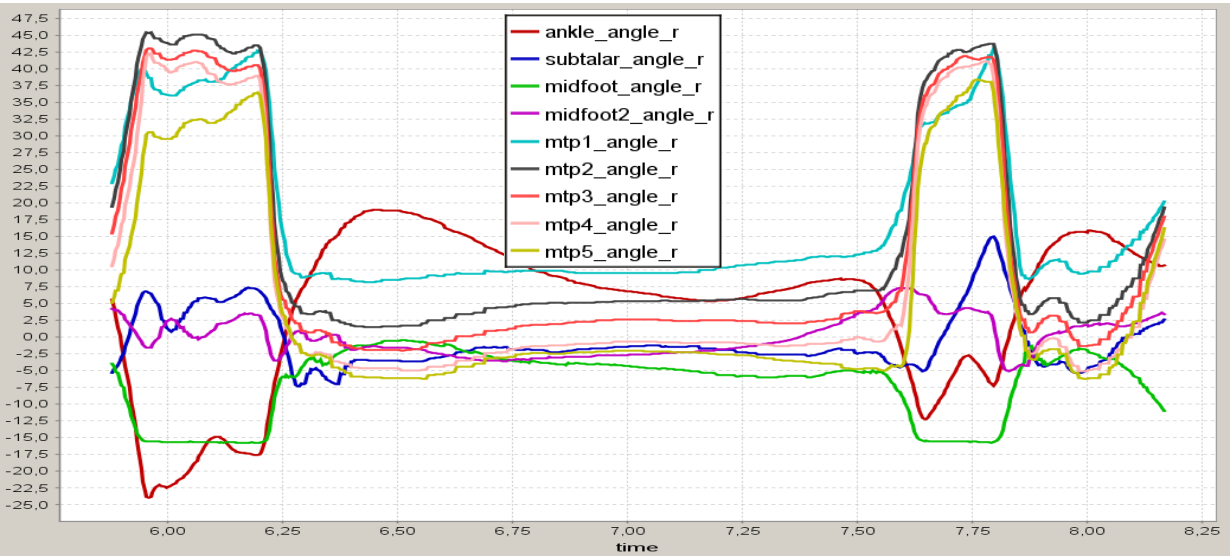

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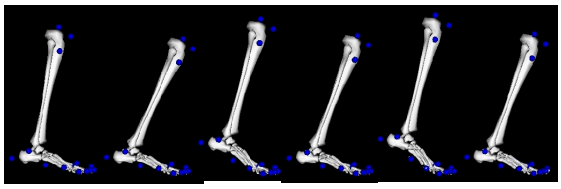

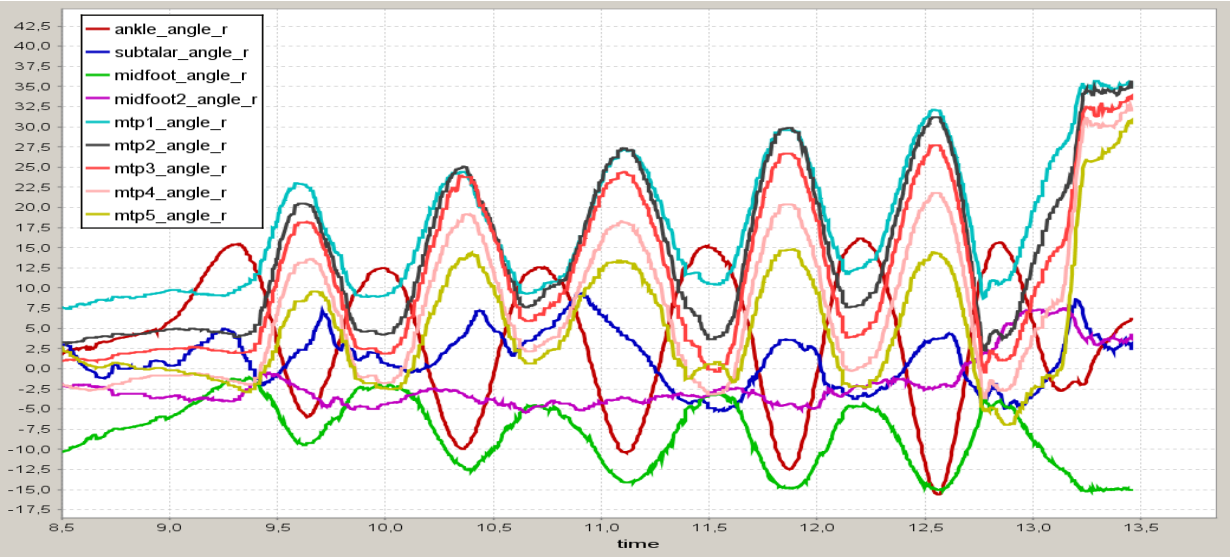

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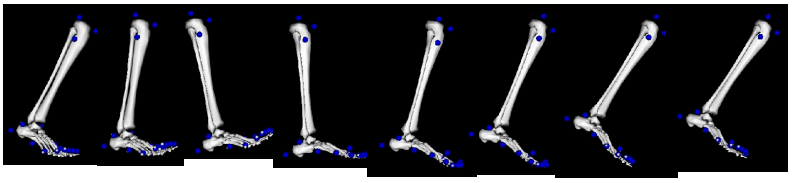
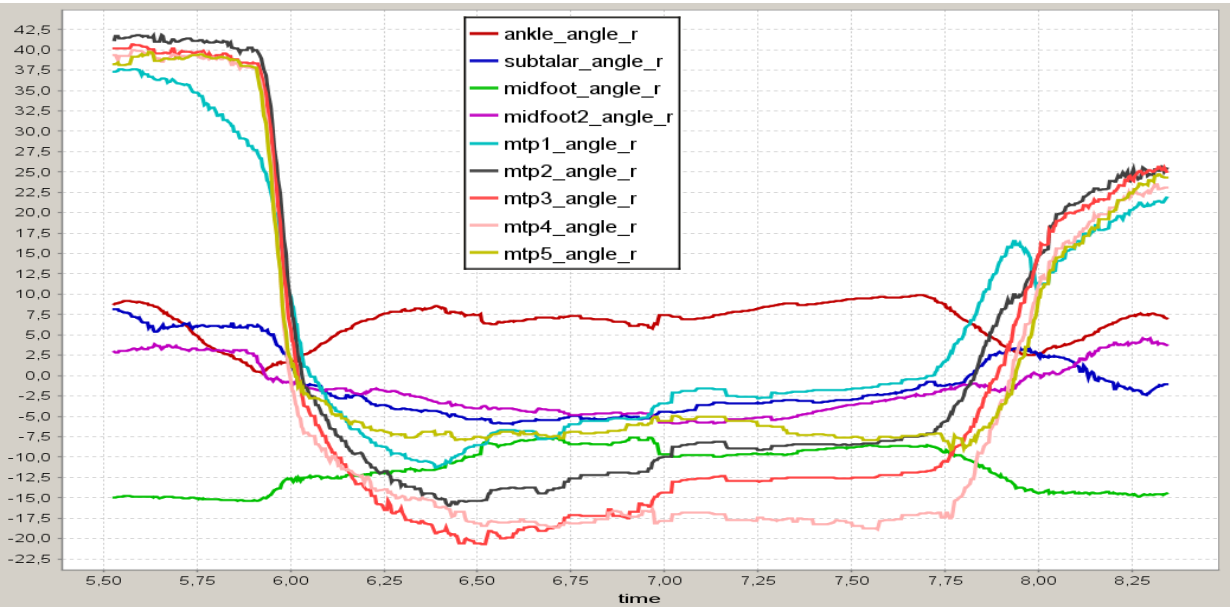


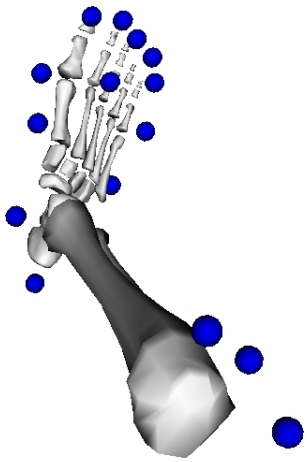


Appendix B

The root mean square experiments results

The Root Mean Square Error experience
Biomechanical simulation of movements (31 trials)
Using 14 musculoskeletal Models:

Ankle_humSubtalar_2xFlexible_5xToes(Tr.Ob.Axis)
Ankle_humSubtalar_2xFlexible_5xToes(Ob.Axis)
Ank._humSubt._2xFlex._2xToes(Tr.Ob.Axis)
Ank._humSubt._2xFlex._1xToe(Ob.Axis)
Ank._humSubt._2xFlex._1xToe(Tr.Axis)
Ank._humSubt._2xFlex._NoToes
Ank._humSubt._2xhumFlex._NoToes
Ank._humSubt._1xFlex._NoToes
Ank._humSubt._NoFlex._NoToes
Ank._functSubt._NoFlex._NoToes
Ank._robSubt._NoFlex._NoToes
Ank._NoSubt._NoFlex._NoToes
NoAnk._NoSubt._1xFlex._NoToes
NoAnk._NoSubt._NoFlex._NoToes



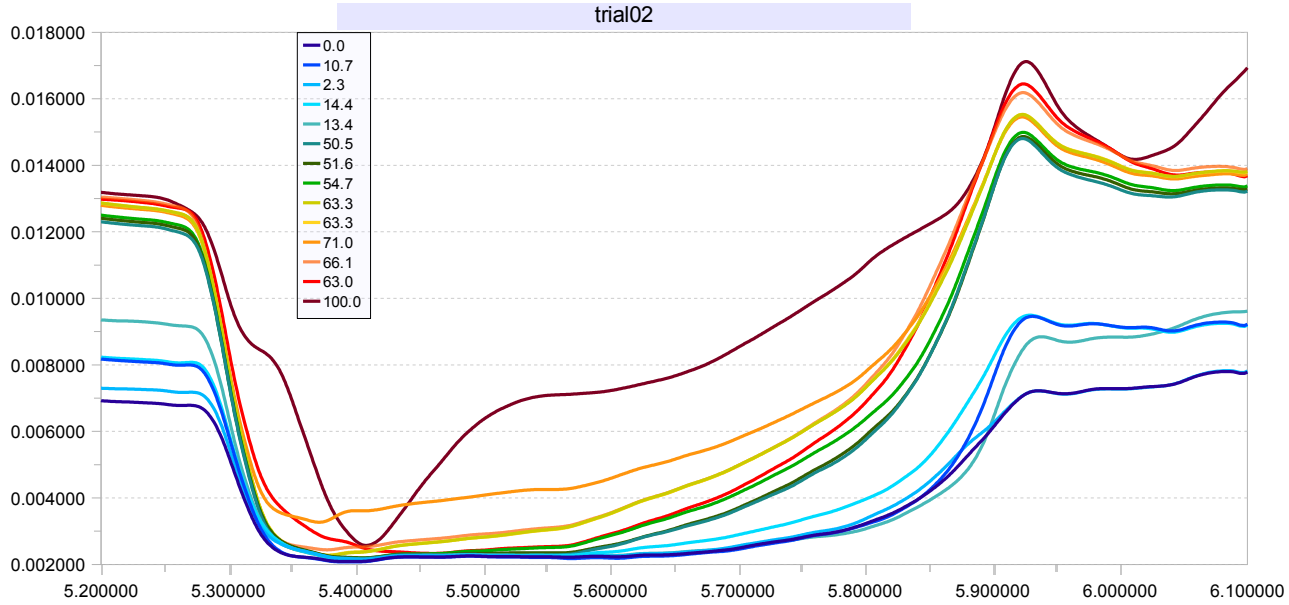
Global Results

Ankle_humSubtalar_2xFlexible_5xToes(Tr.Ob.Axis)
Ankle_humSubtalar_2xFlexible_5xToes(Ob.Axis)
Ank._humSubt._2xFlex._2xToes(Tr.Ob.Axis)
Ank._humSubt._2xFlex._1xToe(Ob.Axis)
Ank._humSubt._2xFlex._1xToe(Tr.Axis)
Ank._humSubt._2xFlex._NoToes
Ank._humSubt._2xhumFlex._NoToes
Ank._humSubt._1xFlex._NoToes
Ank._humSubt._NoFlex._NoToes
Ank._functSubt._NoFlex._NoToes
Ank._robSubt._NoFlex._NoToes
Ank._NoSubt._NoFlex._NoToes
NoAnk._NoSubt._1xFlex._NoToes
NoAnk._NoSubt._NoFlex._NoToes

		Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
TOTAL error surface %		**0.0**	7.4	2.9	10.9	11.8	**36.9**	39.6	42.0	**47.5**	48.4	54.2	**55.7**	56.6	**100**
	difference	-36.9	-29.5	-34.0	-26.1	-25.1	-10.6	-8.0	-5.5	-8.2	-7.3	-1.5	-44.3	-43.4	
walking	trial01	0	9.5	2.5	12.6	13.4	41.0	42.3	45.5	51.6	51.5	51.9	53.4	52.4	100
	trial02	0	10.7	2.3	14.4	13.4	50.5	51.6	54.7	63.3	63.3	71.0	66.1	63.0	100
	trial03	0	12.7	1.4	16.8	11.9	54.8	56.2	60.9	69.1	69.0	76.8	71.7	68.7	100
	trial04	0	11.2	1.9	14.3	12.5	50.2	51.5	55.2	63.3	63.1	71.6	67.3	64.0	100
	trial05	0	9.9	2.0	12.8	13.2	49.1	50.2	53.2	61.8	61.7	68.8	66.1	62.7	100
	trial06	0	10.0	1.9	13.0	12.1	44.1	44.8	47.4	54.3	54.2	61.2	57.4	55.7	100
	trial07	0	9.6	1.9	11.9	13.2	43.4	43.9	46.0	53.4	53.2	60.5	56.2	54.4	100
	trial08	0	8.7	1.7	10.9	11.2	41.3	41.4	42.8	49.8	49.9	55.2	53.9	55.6	100
	subtotal	0	10.3	2.0	13.3	12.6	**46.8**	47.7	50.7	**58.3**	58.2	64.6	**61.5**	59.5	100
		-46.8	-36.5	-44.8	-33.5	-34.2	-11.5	-10.6	-7.6	-3.2	-3.3	3.1	-38.5	-40.5	
jogging	trial09	0	10.0	0.5	11.1	10.2	38.3	39.6	41.7	46.6	46.6	48.2	48.5	49.6	100
	trial10	0	9.5	0.5	11.1	9.0	36.8	38.7	41.0	46.0	46.3	47.6	49.2	50.5	100
running	trial31	0	9.1	0.8	10.7	7.9	38.3	39.2	40.8	43.9	44.1	46.1	47.1	51.2	100
	subtotal	0	9.5	0.6	11.0	9.0	**37.8**	39.2	41.2	**45.5**	45.7	47.3	**48.3**	50.4	100
		-37.8	-28.2	-37.2	-26.8	-28.7	-7.7	-6.3	-4.3	-2.8	-2.6	-0.9	-51.7	-49.6	
turn left	trial11	0	11.6	3.0	17.8	10.7	51.2	57.4	64.2	72.0	73.8	77.7	83.6	83.5	100
	trial12	0	10.5	1.6	15.7	8.3	44.6	50.7	57.3	64.6	66.5	71.9	76.4	76.4	100
	trial13	0	10.7	2.3	14.9	9.8	44.4	48.0	52.3	59.8	60.8	66.4	68.5	68.5	100
	trial14	0	9.7	3.2	15.6	8.8	39.9	43.8	50.4	56.2	57.5	61.2	66.6	67.9	100
	trial15	0	8.4	3.0	13.3	8.8	33.4	39.9	47.2	52.3	54.0	57.6	63.6	64.6	100
	subtotal	0	10.2	2.6	15.5	9.3	**42.7**	48.0	54.3	**61.0**	62.5	66.9	**71.7**	72.2	100
		-42.7	-32.5	-40.1	-27.2	-33.4	-18.3	-13.0	-6.7	-10.8	-9.2	-4.8	-28.3	-27.8	
turn right	trial16	0	9.7	1.5	10.3	14.1	41.5	44.7	46.4	54.2	56.0	51.1	69.9	64.4	100
	trial17	0	5.6	2.7	7.3	17.1	35.8	42.5	46.5	55.2	58.2	49.3	83.5	79.1	100
	trial18	0	9.1	1.5	10.0	14.4	41.5	46.8	50.1	59.4	62.1	54.1	83.3	77.6	100
	trial19	0	8.3	1.5	8.9	13.8	35.8	39.4	41.5	49.9	52.1	47.1	68.4	62.0	100
	trial20	0	7.7	1.7	8.1	14.3	36.8	40.0	41.5	50.7	52.4	47.7	64.5	56.8	100
	trial21	0	8.1	1.2	8.2	12.1	38.4	40.9	41.6	49.7	51.4	45.8	60.7	53.6	100
	subtotal	0	8.1	1.7	8.8	14.3	**38.3**	42.4	44.6	**53.2**	55.4	49.2	**71.7**	65.6	100
		-38.3	-30.2	-36.6	-29.5	-24.0	-14.9	-10.8	-8.6	-18.5	-16.3	-22.5	-28.3	-34.4	
lateral steps	trial22	0	8.1	5.0	11.3	21.4	40.3	44.0	46.7	52.3	54.2	77.8	65.5	64.0	100
	trial23	0	4.9	5.5	9.0	18.3	31.0	35.7	39.1	44.6	46.4	79.8	58.5	55.3	100
	trial24	0	6.9	6.3	11.5	21.0	37.2	40.0	41.7	43.1	44.6	71.6	54.4	56.9	100
	subtotal	0	6.6	5.6	10.6	20.3	**36.2**	39.9	42.5	**46.7**	48.4	76.4	**59.5**	58.7	100
		-36.2	-29.5	-30.6	-25.6	-15.9	-10.5	-6.8	-4.2	-12.8	-11.1	17.0	-40.5	-41.3	
jump	trial25	0	2.1	0.9	3.3	3.5	11.6	12.2	13.0	15.5	15.9	20.1	18.9	24.9	100
	trial26	0	2.8	1.1	4.1	2.9	17.5	17.7	19.1	23.2	23.1	24.8	24.1	27.5	100
	trial27	0	3.0	1.0	4.8	3.4	17.5	17.8	19.1	22.2	22.6	25.7	25.4	29.0	100
	subtotal	0	2.6	1.0	4.0	3.3	**15.6**	15.9	17.1	**20.3**	20.5	23.5	**22.8**	27.1	100
		-15.6	-12.9	-14.6	-11.5	-12.3	-4.7	-4.4	-3.2	-2.5	-2.3	0.7	-77.2	-72.9	
on the toes	trial28	0	2.1	2.2	5.0	5.2	**17.5**	18.1	19.5	**23.0**	23.4	28.0	**27.1**	31.1	100
up down		-17.5	-15.4	-15.3	-12.5	-12.2	-5.6	-4.9	-3.5	-4.1	-3.7	0.8	-72.9	-68.9	
walking with	trial29	0	4.0	9.6	12.7	15.5	45.1	50.0	49.7	55.5	56.3	59.6	66.9	71.5	100
terrain adaptation	trial30	0	4.6	4.8	12.9	12.4	37.1	38.1	37.8	40.2	40.3	43.6	42.3	53.4	100
	subtotal	0	4.3	7.2	12.8	13.9	**41.1**	44.0	43.7	**47.8**	48.3	51.6	**54.6**	62.5	100
		-41.1	-36.8	-33.9	-28.3	-27.2	-6.7	-3.8	-4.1	-6.8	-6.3	-3.0	-45.4	-37.5	

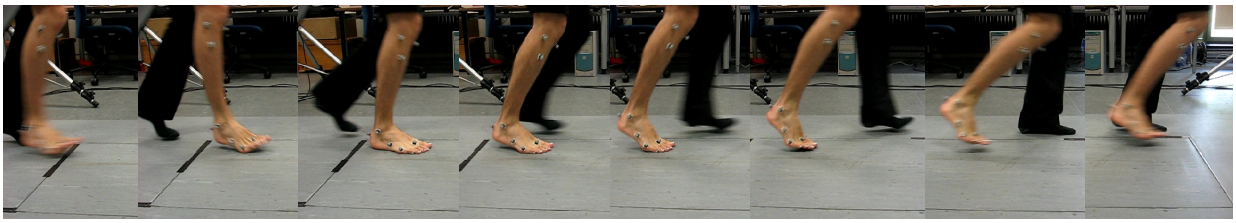
Walking trials Results:

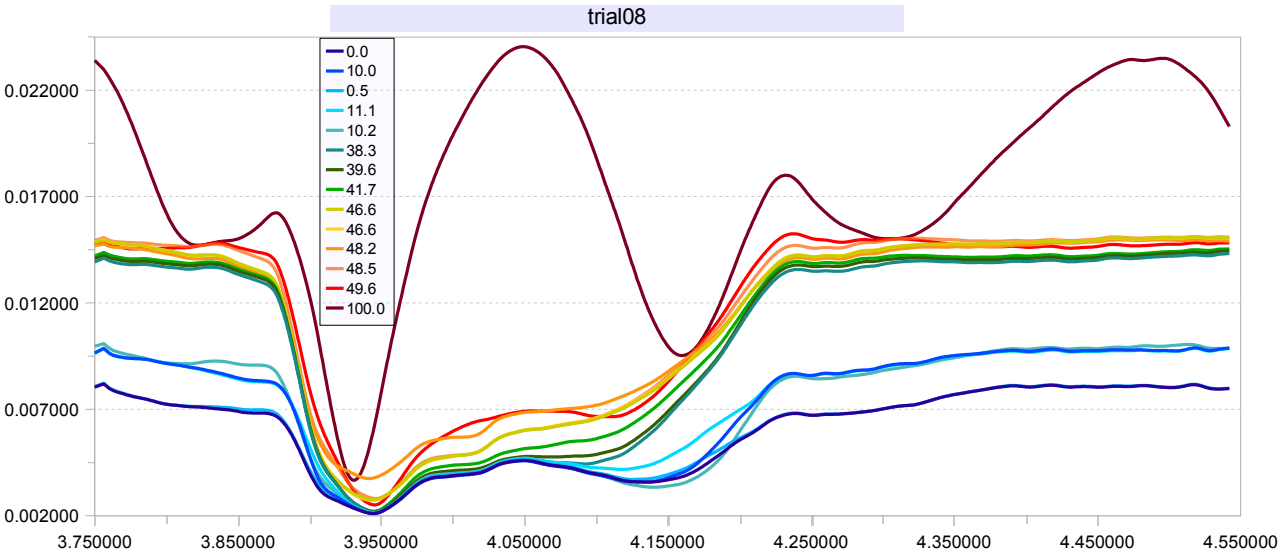
	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial01	0	9.5	2.5	12.6	13.4	41.0	42.3	45.5	51.6	51.5	51.9	53.4	52.4	100
trial02	0	10.7	2.3	14.4	13.4	50.5	51.6	54.7	63.3	63.3	71.0	66.1	63.0	100
trial03	0	12.7	1.4	16.8	11.9	54.8	56.2	60.9	69.1	69.0	76.8	71.7	68.7	100
trial04	0	11.2	1.9	14.3	12.5	50.2	51.5	55.2	63.3	63.1	71.6	67.3	64.0	100
trial05	0	9.9	2.0	12.8	13.2	49.1	50.2	53.2	61.8	61.7	68.8	66.1	62.7	100
trial06	0	10.0	1.9	13.0	12.1	44.1	44.8	47.4	54.3	54.2	61.2	57.4	55.7	100
trial07	0	9.6	1.9	11.9	13.2	43.4	43.9	46.0	53.4	53.2	60.5	56.2	54.4	100
trial08	0	8.7	1.7	10.9	11.2	41.3	41.4	42.8	49.8	49.9	55.2	53.9	55.6	100
Average Error surface %	**0**	10.3	2.0	13.3	12.6	**46.8**	47.7	50.7	**58.3**	58.2	64.6	**61.5**	59.5	**100**
	-46.8	-36.5	-44.8	-33.5	-34.2	-11.5	-10.6	-7.6	-3.2	-3.3	3.1	-38.5	-40.5	



'jogging and running' trials Results:

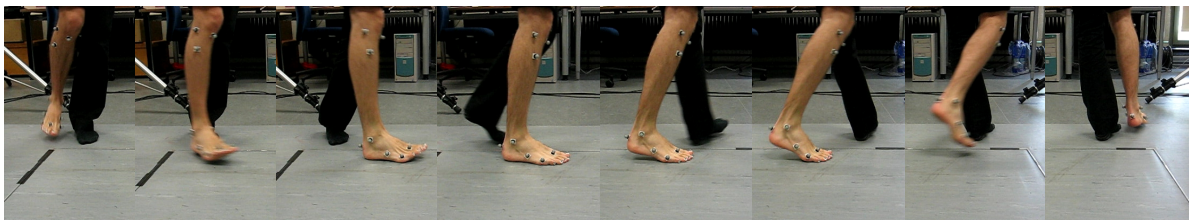
	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial09	0	10.0	0.5	11.1	10.2	38.3	39.6	41.7	46.6	46.6	48.2	48.5	49.6	100
trial10	0	9.5	0.5	11.1	9.0	36.8	38.7	41.0	46.0	46.3	47.6	49.2	50.5	100
trial31	0	9.1	0.8	10.7	7.9	38.3	39.2	40.8	43.9	44.1	46.1	47.1	51.2	100
Average Error surface %	**0**	9.5	0.6	11.0	9.0	**37.8**	39.2	41.2	**45.5**	45.7	47.3	**48.3**	50.4	**100**
	-37.8	-28.2	-37.2	-26.8	-28.7	-7.7	-6.3	-4.3	-2.8	-2.6	-0.9	-51.7	-49.6	

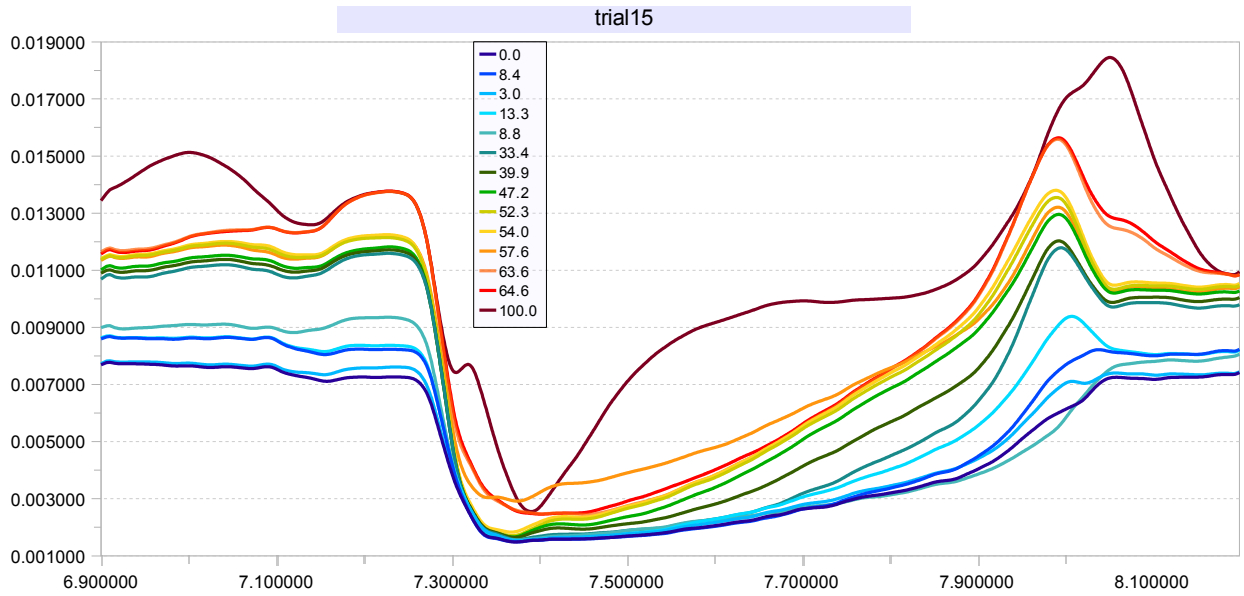




'turning left' trials Results:

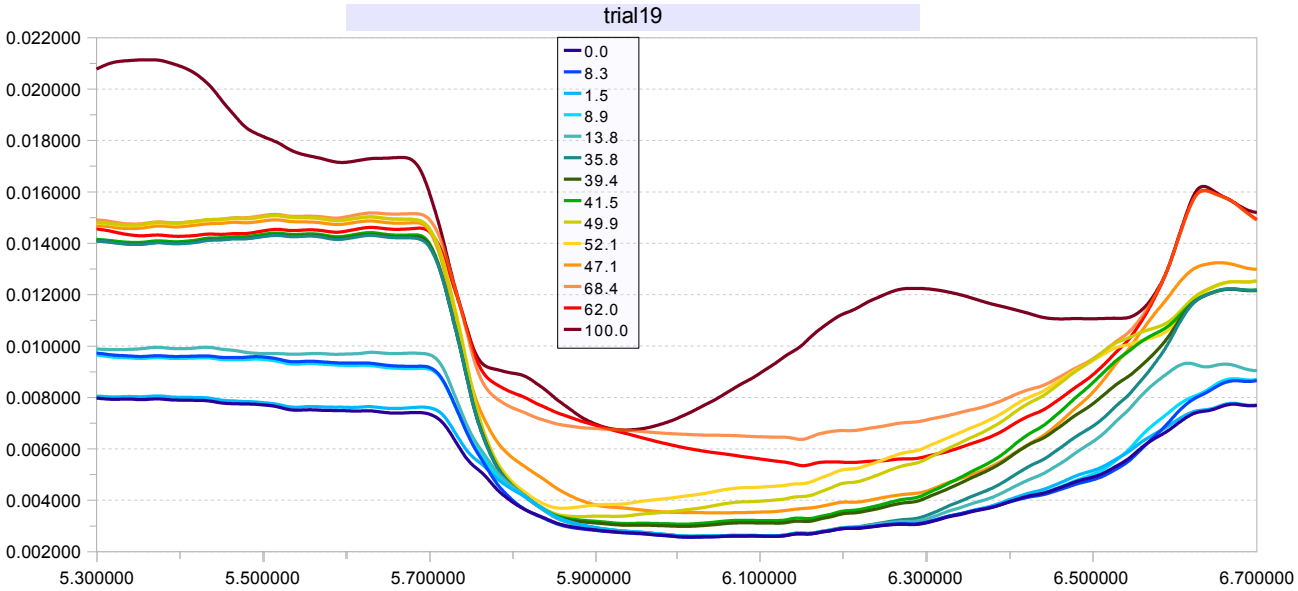
	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial11	0	11.6	3.0	17.8	10.7	51.2	57.4	64.2	72.0	73.8	77.7	83.6	83.5	100
trial12	0	10.5	1.6	15.7	8.3	44.6	50.7	57.3	64.6	66.5	71.9	76.4	76.4	100
trial13	0	10.7	2.3	14.9	9.8	44.4	48.0	52.3	59.8	60.8	66.4	68.5	68.5	100
trial14	0	9.7	3.2	15.6	8.8	39.9	43.8	50.4	56.2	57.5	61.2	66.6	67.9	100
trial15	0	8.4	3.0	13.3	8.8	33.4	39.9	47.2	52.3	54.0	57.6	63.6	64.6	100
Average Error surface %	**0**	10.2	2.6	15.5	9.3	**42.7**	48.0	54.3	**61.0**	62.5	66.9	**71.7**	72.2	**100**
	-42.7	-32.5	-40.1	-27.2	-33.4	-18.3	-13.0	-6.7	-10.8	-9.2	-4.8	-28.3	-27.8	





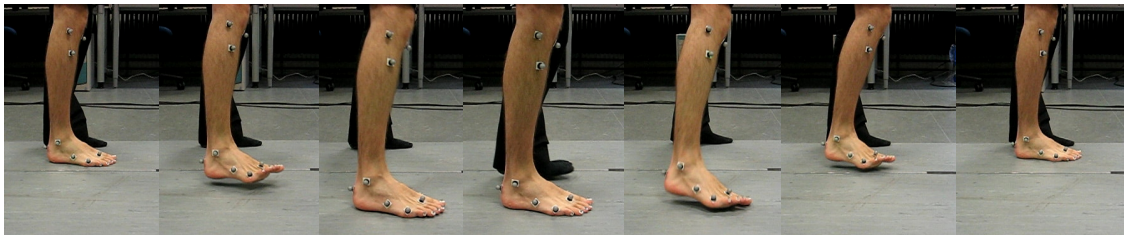
'turning right' trials Results:

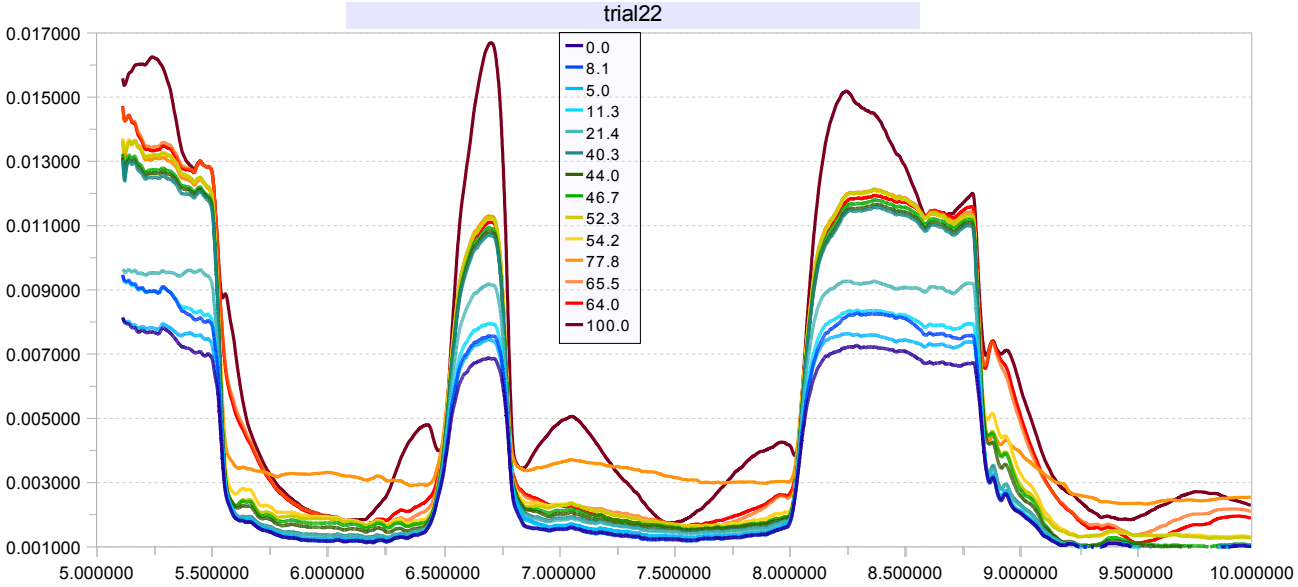
	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial16	0	9.7	1.5	10.3	14.1	41.5	44.7	46.4	54.2	56.0	51.1	69.9	64.4	100
trial17	0	5.6	2.7	7.3	17.1	35.8	42.5	46.5	55.2	58.2	49.3	83.5	79.1	100
trial18	0	9.1	1.5	10.0	14.4	41.5	46.8	50.1	59.4	62.1	54.1	83.3	77.6	100
trial19	0	8.3	1.5	8.9	13.8	35.8	39.4	41.5	49.9	52.1	47.1	68.4	62.0	100
trial20	0	7.7	1.7	8.1	14.3	36.8	40.0	41.5	50.7	52.4	47.7	64.5	56.8	100
trial21	0	8.1	1.2	8.2	12.1	38.4	40.9	41.6	49.7	51.4	45.8	60.7	53.6	100
Average Error surface %	**0**	8.1	1.7	8.8	14.3	**38.3**	42.4	44.6	**53.2**	55.4	49.2	**71.7**	65.6	**100**
	-38.3	-30.2	-36.6	-29.5	-24.0	-14.9	-10.8	-8.6	-18.5	-16.3	-22.5	-28.3	-34.4	



'lateral steps' trials Results:

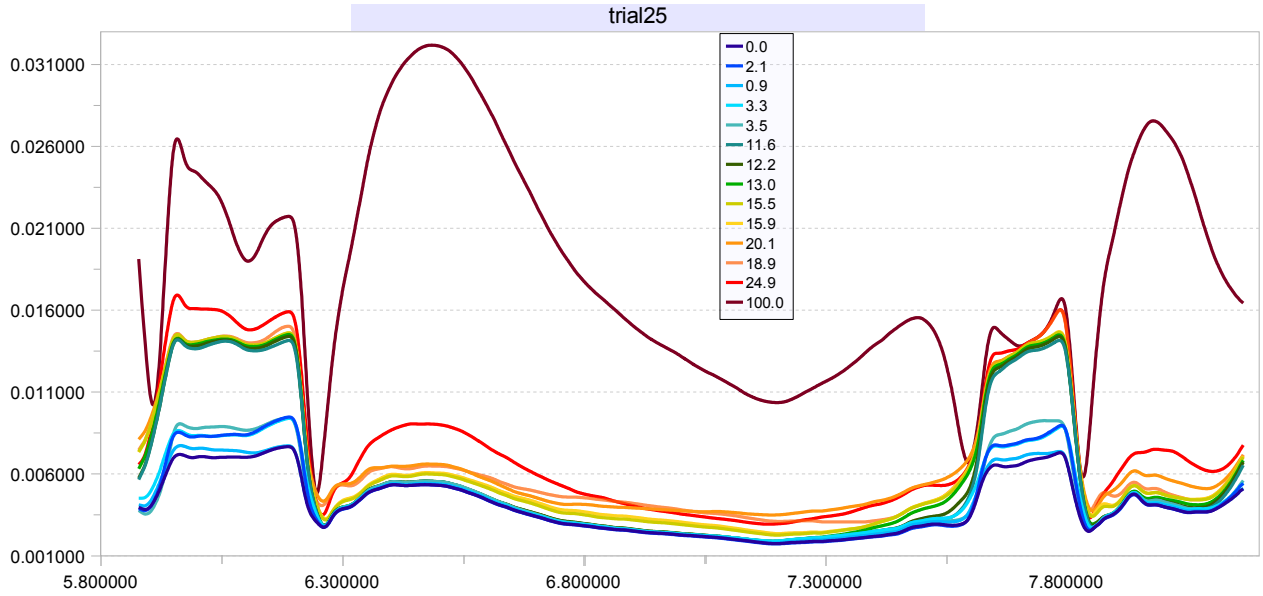
	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial22	0	8.1	5.0	11.3	21.4	40.3	44.0	46.7	52.3	54.2	77.8	65.5	64.0	100
trial23	0	4.9	5.5	9.0	18.3	31.0	35.7	39.1	44.6	46.4	79.8	58.5	55.3	100
trial24	0	6.9	6.3	11.5	21.0	37.2	40.0	41.7	43.1	44.6	71.6	54.4	56.9	100
Average Error surface %	**0**	6.6	5.6	10.6	20.3	**36.2**	39.9	42.5	**46.7**	48.4	76.4	**59.5**	58.7	**100**
	-36.2	-29.5	-30.6	-25.6	-15.9	-10.5	-6.8	-4.2	-12.8	-11.1	17.0	-40.5	-41.3	





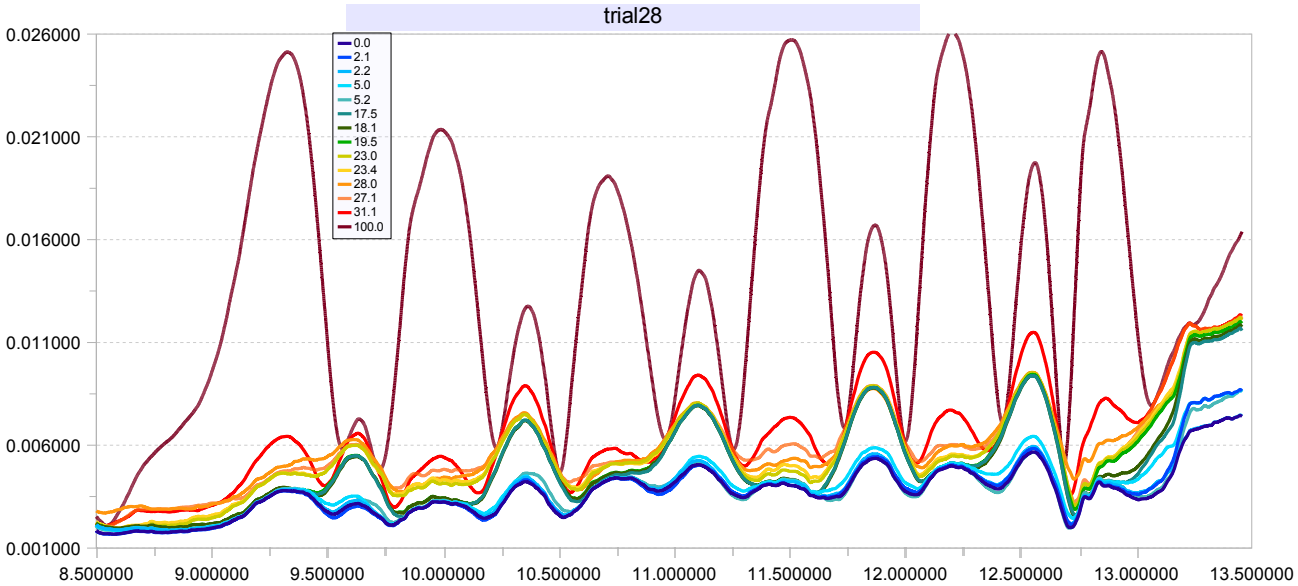
'jumping' trials Results:

	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial25	0	2.1	0.9	3.3	3.5	11.6	12.2	13.0	15.5	15.9	20.1	18.9	24.9	100
trial26	0	2.8	1.1	4.1	2.9	17.5	17.7	19.1	23.2	23.1	24.8	24.1	27.5	100
trial27	0	3.0	1.0	4.8	3.4	17.5	17.8	19.1	22.2	22.6	25.7	25.4	29.0	100
Average Error surface %	**0**	2.6	1.0	4.0	3.3	**15.6**	15.9	17.1	**20.3**	20.5	23.5	**22.8**	27.1	**100**
	-15.6	-12.9	-14.6	-11.5	-12.3	-4.7	-4.4	-3.2	-2.5	-2.3	0.7	-77.2	-72.9	



'on the toes' trials Results:

	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial28 Error surface %	**0**	2.1	2.2	5.0	5.2	**17.5**	18.1	19.5	**23.0**	23.4	28.0	**27.1**	31.1	**100**
	-17.5	-15.4	-15.3	-12.5	-12.2	-5.6	-4.9	-3.5	-4.1	-3.7	0.8	-72.9	-68.9	



'terrain adaptation' trials Results:

	Toes design					Flexibility design			Subtalar design			Ankle design		Ref.
trial29	0	4.0	9.6	12.7	15.5	45.1	50.0	49.7	55.5	56.3	59.6	66.9	71.5	100
trial30	0	4.6	4.8	12.9	12.4	37.1	38.1	37.8	40.2	40.3	43.6	42.3	53.4	100
Average Error surface %	**0**	4.3	7.2	12.8	13.9	**41.1**	44.0	43.7	**47.8**	48.3	51.6	**54.6**	62.5	**100**
	-41.1	-36.8	-33.9	-28.3	-27.2	-6.7	-3.8	-4.1	-6.8	-6.3	-3.0	-45.4	-37.5