The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

The Design of an Anthropomorphic Dexterous Humanoid Foot

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***Abstract*—**
The human foot serves three main functions; adapts to contours of ground, absorbs shock impacts and stores and releases energy. Despite significant development of humanoid robots the foot has seen little research and as a result most bipeds do not walk in a humanlike manner.

In this work a study of the human foot is conducted to determine how each of these is achieved. The paper then describes the design, construction and testing of a fully articulated humanoid foot which has the same functionality as the human foot.

I. INTRODUCTION

The first evidence of the existence of the anatomical foot dates from some 370 million years ago [1] when tetrapods first developed rudimentary legs and feet allowing them to propel themselves out of water. Since this time of course, the foot has continued to evolve with different species adopting unique foot designs. The modern human foot appears to have resulted from an evolutionary divergence from apes approximately 5 million years ago [2]. The evolutionary direction of the human foot was dictated by its intended function with the first appearance of a foot for purely bipedal locomotion appearing approximately 3.7 million years ago [2].

Historically, what became the modern human foot was used for both locomotion and grasping [3], as is still the case with many primates and some humans. However, as humans evolved to be true bipeds so the function of the feet changed. The human foot has three main functions, adapting to the contours of the ground [1] absorbing shock and impact forces [1] and storing and releasing energy to increase locomotive efficiency [3][4].

Over the past two decades the development of artificial humanoids in the form of robots has advanced rapidly and there are now numerous examples of humanoid robots such as P3 [5], ASIMO [6], JOHNNIE [7], HRP-2 [8], H6 [9], KHR-3 [10], SDR-4X [11], iCub [12], WABIAN-2R[13] and many more. Despite their highly advanced kinematics and capabilities, most of these machines have simple feet with little of the functionality of the human foot. The most notable exception is the impact absorbing qualities of the foot. P2, HRP-2 and BHR-2 all use rubber bushes at the ankle [14] to prevent impact forces being transmitted from the foot to the rest of the robot.

Typically robots do not walk in a humanlike manner instead tending to walk with the soles of their feet parallel to the ground at all times [13]. A human, however, walks with a repeating pattern, where weight is taken by the heel, on landing, is transferred to the flat of the foot and then to the toes prior to push off. There have been attempts to duplicate this technique in robots such as BHR-2 where a solid foot is chamfered at the front and rear to produce three distinct contact surfaces [14]. WABIAN-2R[13] includes a passive forefoot which allows the foot to pitch forwards prior to push-off and the pneumatic robot BIPMAN [15] achieves the same ability using a 1 d.o.f. actuated toe as does the humanoid robot LOLA [16]. The Toyota humanoid robot [17] also has an actuated 1 d.o.f. toe on each foot allowing it to walk and run on its oversized forefoot. The toe, ankle and knee joints use compliance control to absorb impacts forces. To replicate the energy storage capacity of the human foot Secord investigated the use of polymer actuators to store energy in an artificial foot [18]. Seo et al. [19] modelled a biomimetic foot which showed in simulation how a multi d.o.f. foot could adapt to uneven terrain and also demonstrated the elasticity found within the foot.

The development of a mechanical foot may have applications in the development and testing of human footwear. This is often carried out in line with a set of American standards [18] which use drop and compression tests in order to assess the shock absorbing qualities of new shoes.

However, this technique does not provide any indication as to how the shoes might perform in actual use. To determine this, manufacturers commission 100s of testers to wear their products in normal use [21]. At regular intervals the shoes are studied for signs of wear or damage. Observations made are then fed back into the design. To maximise the validity of the results, manufacturers try to ensure that the feet of the testers cover as broad a range of shapes and sizes as possible, however, this can be difficult to achieve. It may be that a mechanical foot which can be modified to include these differences may provide an alternative solution, however, it would require that the artificial foot was an accurate representation of the human foot.

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This paper will explore the operation of the human foot and then use this to produce a mechanical foot with the same functionality as a human foot.

II. THE HUMAN FOOT

Analysing the behaviour of the human foot has proven difficult as motion between bones occurs in all planes and the axis of joint rotations move in a highly complex manner as the foot deforms [1]. Also there can be enormous variation in the motion of two apparently similar feet performing the same task. Nester et al. [22] used a rig to produce walking motion in cadaver feet. They showed that the joint angles were quite different for each sample foot. One theory on these large variations is that the foot is "work in progress" and is still evolving [2], it may be that in 1 million years the human foot becomes more uniform [2].

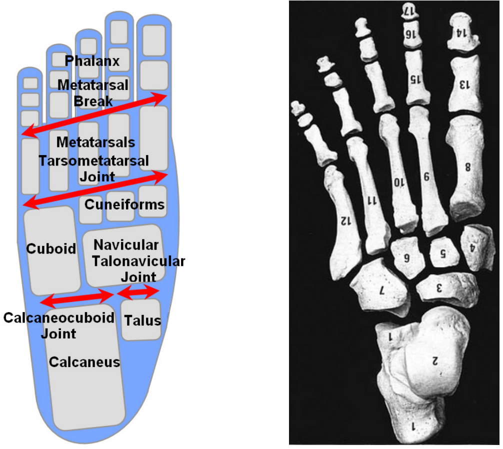


Figure 1 - Bones and significant joints of human foot.

The human foot has 26 bones [2], Figure 1, and 31 major joints [23]. Defining the toe joints is relatively straightforward, however, the joints in the mid and hind foot are more difficult to define. The Navicular and Cuboid bones are not physically attached but motion between them is so small that they can be considered as one [3]. The three Cuneiform bones form the foot's transverse arch [24] and along with the Metatarsals and Cuboid form the Tarsometatarsal joint. The Tarsometatarsal joint acts together with the hindfoot joints (Calcaneocuboid and Talonavicular) to form the longitudinal arch. This is the most significant arch in the foot [3] and is secured by the long Plantar Ligament which connects from the heel to the metatarsal heads [4].

Intuitively it would seem that the foot would be stronger if the midfoot was formed from a single bone. However, this would be susceptible to damage from ground impacts forces. The use of multiple cartilage covered bones allows small motion between bones [25] allowing the foot to deform elastically and absorbs impact forces [3].

The arches also absorb impacts by flexing, but more significantly they are able to store strain energy and return this in an elastic recoil [4]. This ability provides benefits in terms of energy efficiency and conservation. Ker et al. [4] using cadaver feet showed that the longitudinal arch is the most significant arch in achieving this. The other features of the foot which makes it well suited to enduring repeated impact forces are its flat fleshy pads [3]. Basic foot models assume a tripod support formed by the heel and 1st and 5th metatarsal heads [2] and it is significant that the largest pads are found at these locations.

The toes attach to the foot at the metatarsal break, a line formed by the metatarsals heads. This series of joints is angled at 50-70° to the longitudinal foot axis [25] and the proximal toe joints are able to move -30→90° for the Hallux (big toe) and -50°→90° for others. The main function of the toes is to improve leverage and increase the foot's weight bearing area [3]. The Hallux takes 50% of the force applied to the toes with the remainder being spread in increasingly smaller amounts between the 2nd-5th toes [3]. In the moments prior to push off only the toes are in contact with the ground, however, at this point most weight has been transferred from the foot and the toes are not required to support the entire body [3].

III. ROBOT FOOT DESIGN

From the study of the human foot it is possible to identify its most important functions. These are:

- The ability to adapt to contours of ground
- The ability to absorb impacts
- The storage and release of energy

These features form the basis of the mechanical design.

A. *Kinematics*

Theoretically more degrees of freedom mean the foot is better able to adapt to an uneven terrain. However, as has been seen, many of the joints move in a different manner for different individuals or their motion is so small as to be considered inflexible. The joints identified as being the most significant are shown in Figure 2.

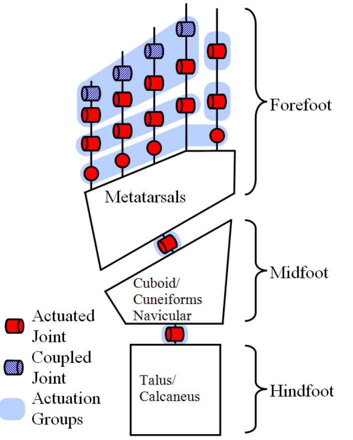


Figure 2 – Robot foot joint and actuation groups

The toes are fully articulated with three joints in each with the exception of the hallux which has just two. As is the case with the fingers the distal and medial toe joints are coupled and this feature is included in the design.

The Metatarsals are represented by a single solid section of material onto which each toe is mounted to form the Metatarsal Break. The angle of the Metatarsal Break is 60°. Each toe, except the 2nd, is attached via a flexible joint which replicates the lateral motion of the toe caused by movement of the Metatarsals. The 2nd toe lacks this lateral metatarsal motion as empirical observations indicated that the other toes tended to use the 2nd toe as central datum about which they moved.

As the inter-bone motion in the Midfoot is small this section is formed from a single solid section. This is attached to the forefoot via a 1 d.o.f. joint which represents the Tarsometatarsal joint. Similarly the hindfoot consists of a single section representing the Talus and Calcaneus bones. This attaches to the midfoot via 1 d.o.f. joint in place of the Calcaneocuboid and Talonavicular joints. The hindfoot also provides a mounting point to attach the foot to the leg.

The articulations in the foot not only help it to adapt to uneven terrain but also form the transverse and longitudinal arches. Of the two, the longitudinal arch is more important in storing energy [4]. This arch is included in the design and is formed by the hindfoot/midfoot and the midfoot/forefoot joints.

B. Flesh

The ability of the foot to adapt to uneven terrain and absorb impacts is achieved through flexibility of the foot, as shown by Seo et al. [19]. However, it also relies on deformation of the foot's flesh.

An engineering material does not exist that has both the rigidity required to form the main foot structure and the compressibility and deformability of flesh. It was there necessary to construct the foot from two materials. Just like a human foot the mechanical foot has a rigid internal skeleton and a soft external "flesh".

The material selected as the "flesh" needed to have characteristics similar to real flesh and skin. The Shore hardness of flesh varies from 20-40 depending upon its location on the foot [26]. The material ultimately selected was a room temperature vulcanizing (RTV) silicone rubber with a Shore hardness of 20. Individual pieces of silicone flesh were moulded and then bonded to the foot skeleton to give the foot the correct shape and areas of fleshy bulk, Figure 3.

It can be seen that the foot includes the large fleshy pads found on the heel and metatarsal heads as they are vital to the impact absorbing qualities of the foot. The flesh of the midfoot base is actually thicker on the mechanical foot than that of a human foot. As midfoot is formed from a solid section rather than the deformable group of bones found in nature this section is less tolerant of impact forces than a human foot. However, by adding a thicker section of flesh to the midfoot the same overall goal can be achieved.

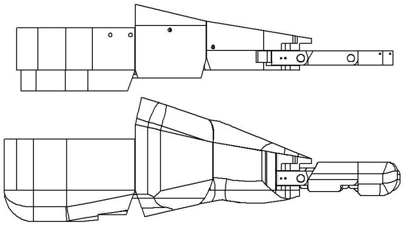


Figure 3 – Robotic skeletal and "flesh" structures

C. Arches

When the human foot makes contact with the ground during walking and running the arch becomes flattened. To observe this effect a series of photographs were taken during walking, Figure 4. It can be seen that on impact with the ground the arch is raised (a), as weight transfers to the foot the arch lowers (b) before recoiling as the foot begins to lift (c). From the photographs it was possible to determine that the arch lowered by approximately 5mm as loading is applied.

(a) (b) (c)

Figure 4 – Flattening of arch during walking

During this process energy is stored in the Plantar Ligament which behaves much like a spring. If larger forces are applied to the foot, for example during running or jumping the arch will flatten to a greater degree.

On the mechanical foot the longitudinal arch is formed by the hindfoot/midfoot and midfoot/forefoot joints. By adjusting the relative angles of these two joints the foot arch can be raised and lowered as seen in Figure 5.

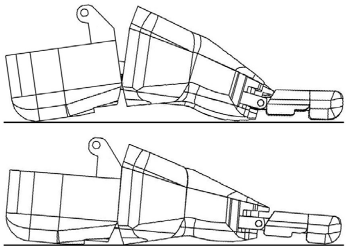


Figure 5 – Foot with lowered and raised arch

The foot includes two pairs of springs located rear and midfoot which have the same function as the Plantar

Ligament allowing energy to be temporarily stored in the foot before releasing to when required.

D. Material

The flesh of the foot is formed from silicone. However, the skeleton needed to be constructed from a stronger material. Aluminium was selected as the most appropriate material due to its yield strength being greater than that of bone and the fact it can be machined easily and at low cost.

However, the initial foot prototype is actually constructed from Acrylonitrile Butadiene Styrene (ABS). This structural polymer has an ultimate tensile strength of 30-50Mpa which is well below that of bone which has a UTS of 130Mpa. The decision to use ABS was based primarily on the fact that parts could be constructed very rapidly and at very low cost using a rapid prototyping machine. This allowed the design to be constructed tested and redesigned very quickly.

Clearly when constructed from ABS the robot foot is only likely to be 25-35% as strong as a human foot meaning it would be unable to support the 70kg load of a typical human. However, initial testing of the artificial foot would only consider the kinematics, dexterity and overall function. This meant that tests could be conducted using scaled down loadings. Once proven a final foot could be constructed from a material able to withstanding the higher loads.

E. Actuation and Under-Actuation

As in the hand, each joint of the foot is not powered by unique muscles but instead a single muscle attaches to several joints [23]. As the human hand is required for grasping we learn the complex control needed to perform dexterous motions. However, the function of the modern human foot requires less dexterity and so the ability to control individual joints is rarely learnt [3]. This leads to great differences in foot dexterity between subjects and often those born without upper limbs are capable of highly dexterous tasks using their feet [3] e.g. grasping, painting, opening containers etc.

These huge variations in foot dexterity mean there is no definitive description of which joints can and cannot be move individually and this presented a problem during the design of the mechanical foot. Actuating each of the intended 20 joints individually would be highly complex, requiring a large number of actuators and would be unrepresentative of a human foot. Instead joints would need to be grouped so that some joints were coupled.

Two methods were used to determine how the joints would be groups. The first method involved video analysis of the foot during walking. Filmed from multiple directions the footage allowed major joint motions to be identified and grouped. The second method involved asking a small sample group of subjects (5 persons) to determine which joints they were able to consciously move. Whilst it is accepted that this sample is not rigorous from this analysis the most suitable groupings were established as seen in Figure 2. The greatest degree of independent dexterity appeared to be in the Hallux with individual manipulation of the other toes appearing difficult or impossible.

The result is the mechanical foot has seven independently drivable joints or joint groups requiring a total of seven actuators. Due to space limitations in the forefoot all of the electric motor actuators are mounted in the hindfoot with power being fed to the joints via Ultra High Molecular Weight Polyethylene (UHMWPE) tendons [27].

F. Sensors

To allow closed loop position control of the joints/joint groups the angles were measured using small locally mounted sensors (Austria Microsystems AS5040 10-bit programmable magnetic rotary encoder). This Hall Effect sensor monitors the rotation of a diametric magnet at the centre of joint rotation and uses this to give an incremental indication of joint motion.

G. Control

The foot is controlled using boards initially developed for the iCub. These include actuator power drivers and DSP controllers and are connected to a PC via a CAN-USB relay. The DSP provide PID control which was tuned experimentally.

Flexion and extension of all joints in the forefoot is performed by the motors providing 0.5Nm of torque. The joints used to form the arch use springs to replicate the Plantar Ligament. These springs cause the arch to rise, this is lowered and the springs tensioned as load is applied to the foot. However, these joints are not purely passive and it is possible to control the arch height. For this reason the two midfoot joints include a motor (1.5Nm) and spring operating antagonistically to allow both controlled and passive motion.

H. Ankle

The foot does not currently include an actuated ankle joint, however, future options will include testing with an industrial robot to replicate the behaviour of the human leg and ankle.

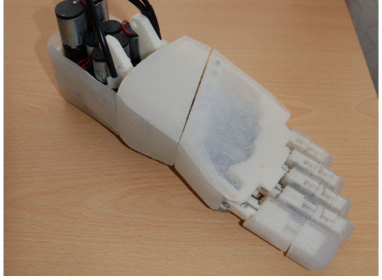


Figure 6 – Completed foot

The completed foot can be seen in Figure 6. It is 263mm long and has a mass of 1.05kg.

IV. EXPERIMENTATION

Experiments were conducted to determine how the mechanical foot behaves compared with a real human foot. This was achieved by evaluating the relative flesh deformation and energy storing ability.

A. *Flesh Stress/Strain*

The stress/strain characteristics of human flesh are difficult to define as it varies with foot location, age and between individuals 0. Human flesh is defined as a viscoelastic material meaning that it does not have a unique Young's modulus. Edsberg et al. 0 obtained stress/strain data for flesh samples and showed that the Young's modulus varied with the speed at which force was applied. The results of these tests are shown in Figure 7 for four different force velocities.

The flesh used on the mechanical foot is formed from silicone which is a homogenous elastic material and therefore has a single Young's modulus. In order to compare the characteristics of the artificial flesh with human flesh stress/stain data was obtained for a sample of the silicone flesh using the procedure employed by Edsberg et al, Figure 7.

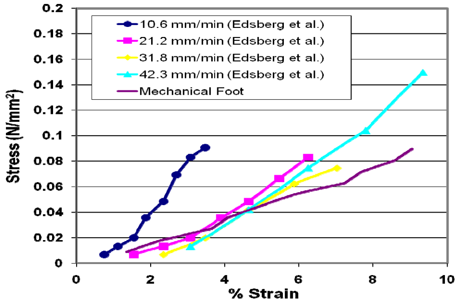


Figure 7 – Flesh stress vs % strain relative to uncompressed flesh

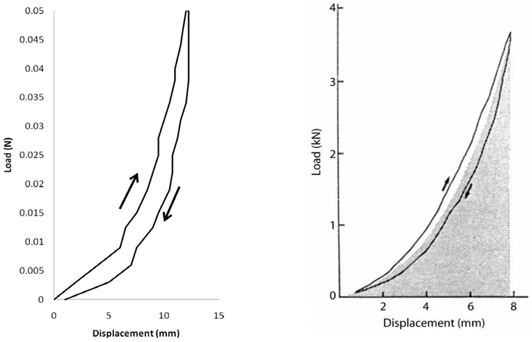
It can be seen that the gradient of the stress/strain plot for the artificial flesh is broadly similar to that of human flesh, particularly at low impact velocities. The human flesh has a Young's modulus of 1.5-3MN/m^2 compared to the silicone which is measured to be 1MN/m^2. The fact that the artificial flesh is slightly more deformable is beneficial as the solid midfoot does not absorb impacts, as was described in section III.B.

B. *Arch Behaviour*

Ker et al. [4] describe an experimental procedure to assess the spring of the foot arch. The foot is positioned on two small trolleys one located at the heel and the other at the metatarsal heads. A vertical force is then applied downwards at the ankle. This causes the arch to flatten out and the distance between the trolleys to increase. The force in then released and the arch will recoil.

The above procedure can be used to experimentally determine the relationship between force applied and the displacement of the arch. Ker et al. observed that the arch of cadaver feet moved 8mm when a 3.6KN force was applied. They also observed a hysteresis when the force was released, indicating that a proportion of the energy is lost.

The experimental procedure was performed with the mechanical foot. For this test the arch was set to operate in a purely passive manner. The force/displacement relationship can be seen in Figure 8.



(a) (b)

Figure 8 – Arch displacement test for mechanical foot (a) and data from Cadaver foot Ker et al. (b)

It can be seen that the force required to lower the arch is significantly less than Ker et al. measured for a cadaver foot. This difference is wholly expected and is the due to the comparatively low forces generated by the springs in the mechanical foot compared to the actual Plantar Ligament. The reason for this is that as described in section III.D the robot foot does not have the same structural strength as a human foot due to the ABS material used. As was mentioned valid results could still be obtained by scaling down the forces applied to the mechanical foot. This was proven to be the case and the profile obtained is broadly similar to that observed in a cadaver foot. The same hysteresis discovered by Ker et al. can also be seen in the robot foot.

C. *Adaption to Uneven Terrain*

Analysing the ability of the foot to adapt to uneven terrain mathematically is highly complex due to the infinite potential scenarios. Instead an experimental approach was use. The ankle joint was mounted to a stationary rig via a universal joint and then lowered onto a flat surface. The process was repeated with a series of 10mm x 10mm aluminium blocks of varying thicknesses placed on the surface so as to make contact with a range of different locations on the foot. In each case a mechanical probe was used to determine if the tripod support described in section II was maintained despite the uneven terrain caused by the introduction of the blocks.

4mm think blocks could be placed anywhere under the foot with no effect on the support tripod as the silicone flesh easily deformed around the blocks. Similarly blocks of up to 15mm thickness placed under the toes had no effect as the toes were able to flex upwards. Blocks thicker than 15mm or placed closer to the proximal end of the toes caused the toes reach their maximum range of motion and this caused the metatarsal break to be lifted off the surface preventing the support tripod.

The support tripod could be maintained a block larger than 20mm were placed at the location of the 1st or 5th metatarsal head. In this instance pronation/supination of the ankle joint allowed the foot to roll and maintain the support tripod. However, when the block was placed at the location of the other metatarsal heads the support tripod could not be produced. This is because the foot does not allow individual motion of the metatarsals. Although it was possible to identify a support tripod this was narrower and therefore less stable than if formed by the 1st and 5th metatarsal head and the heal. This highlights a shortcoming in the current design as unevenness of the ground near the centre of the forefoot can significantly reduce the area and therefore stability of the ground contact. Here the work of Seo et al. [19] is particularly interesting. They showed how motion of individual metatarsal could greatly increase the ability to adapt to uneven ground.

V. CONCLUSIONS AND FUTURE WORK

This paper has described the design of a mechanical foot which aims to replicate the anatomical structure and main functionality of the human foot. This was achieved through a detailed study of the human foot and identification of the most important features and functions. The foot consists of hind, mid and fore foot sections and five toes. It is underactuated with forces being transmitted from motors in the hind foot to each of the joints.

It has been shown that the mechanical foot is able to duplicate the three main tasks of the human foot, namely adapt to contours of ground, absorb shock impacts and storage and release of energy. These abilities are achieved through the multi degree of freedom design, flexing of the foot joints, through deformation of the silicone flesh and through the elastic behaviour of the main longitudinal foot arch.

Future work investigate the introduction of multiple metatarsals to further increase the ability to adapt to uneven terrain and will mount force sensors to the sole of the foot to monitor individual reaction forces.

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