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Design of a mechanical knee joint for an exoskeleton

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Abstract. The main problem of designing a lower limb exoskeleton for healthy people is allowing unconstrained movement along with providing sufficient load carrying capability. It is not a simple task since most of the human body joints have more than one degree of freedom. A designed mechanical equivalent should imitate these movements being outside the human body. Due to this, the mechanical joints must provide shortening or elongation of the structure during load carrying. Authors present biomechanical analyzes of a knee joint and propose a design of a mechanical equivalent of this joint that can be applied in exoskeletons. Additionally, laboratory trials proved suitability of this solution.

1 Introduction

The exoskeletons that will strengthen a human body were carried out since the 60's of the XX century beginning in the automotive industry.
This idea was evaluated and robots that copied human body movements were developed. Some of the designs focused on full-body exoskeletons and some on partial solutions. Exoskeletons have applications in industry, medicine, and military. Each of these branches has different demands regarding e.g. target, usage scenarios, users, and power supply [1].

A person wearing an exoskeleton can still be seen as a super-cyborg idea from SciFi movies. The fact is that in many R&D centers solutions are developed for rescue services and soldiers [2].

The problem is creating an ergonomic device that would allow for walking, running etc. within one design. An ergonomic device is the one that assures unloading of the musculoskeletal system, secures the natural range of motions, prevents from injuries, strengthens a human body. One of the approaches is a passive exoskeleton that, by providing additional support for the load increases the energy efficiency [3].

When a healthy human being is to use the exoskeleton, an additional problem occurs – assuring a sufficient range of movement along with load carrying capability.

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A mechanical structure should not limit the natural range of movement even when a person makes more complicated movements. Body joints often have multiple degrees of freedom (DOFs) like, e.g. a hip joint or an ankle joint. That is the reason why using exoskeletons with simplified joints (with one DOF) decreases drastically the range of movement. It is not possible to copy exactly human body joints and obtain satisfying results since their axes and points of rotation are inaccessible.

While observing human body motion, it can be noticed that limbs seemingly shorten and elongate and that the axis of joint rotation changes its position. Therefore, to design an ergonomic exoskeleton joints that can provide this range of motion are to be designed.
Authors during participation in a grant entitled „An exoskeleton compatible with the individual battle system TYTAN" (grant no. DOBR/0037/R/ID1/2012/03) developed some solutions for hip and knee joints. At that time an ankle joint was not considered to be active. Future works showed a great potential in the ankle joint which is the first/last one that transfers load from/to the ground. Due to this it gives a chance to improve the energetic efficiency of the system and its impact on the human body. The challenge is that the human ankle joint is very complicated in its structure [4].

2 Anatomy of the knee joint

A foot is an important body part when it comes to locomotion. Its basic functions are:

- Support – load transfer;
- Shock absorption;
- Locomotion.

In a foot there are 33 joints and three of them play the most important role during walking: the talocrural joint, the subtalar joint and the inferior tibiofibular joint. All of them together are responsible for dorsiflexion and plantarflexion of the foot.

They have significant range of motion. Eg. for active people in age 18-40 they are given in figure 1 [5][6].

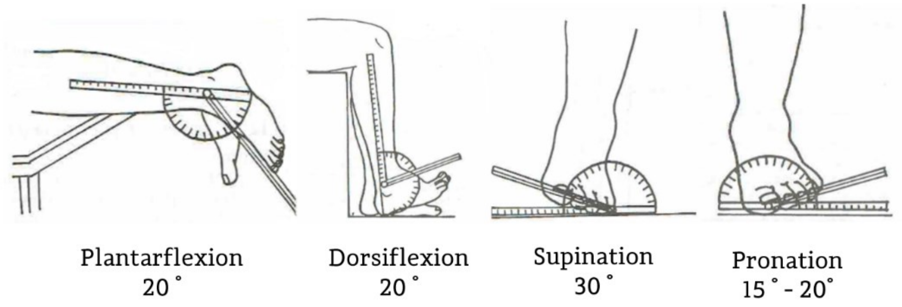

Fig. 1. Estimated standard movement range for an ankle joint

3 Knee joint in the exoskeleton

To imitate human motion accurately mechanical axes of rotation should coincide anatomical axes of rotation. Each inaccuracy has negative impact on body energy consumption [7]. For the upper axis of rotation, it is fairly easy to define its orientation but for the lower one it is not. The center of rotation for supination/pronation movements is inside the foot. The mechanical joint is offset by length w (see fig. 2). Performing this movement causes change in distance between axis of rotation and exoskeleton sole. A user will feel it as shortening of the structure by length X and as a result a pressure acting on the body and movement limitation. This situation is depicted in figure 2.

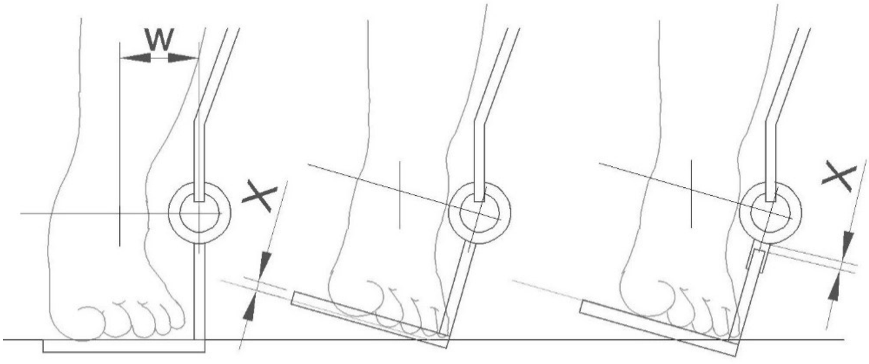

Fig.2 Leg shortening during supination movement

In order to counteract this problem, the mechanical joint or other structure member should be able to compensate this change in length.

Most of the existing solutions is too rigid in this DOF or do not have this flexibility at all. It is not acceptable when the exoskeleton shall be used on uneven surfaces.

The simplest idea to solve this obstacle would be to use additional translational joint as length compensator. This is not a good idea though because it leads to situation where during supination and during contact with the ground all the load will be transferred via musculoskeletal system. This can result in serious injuries.

For that reason, authors made an effort to find more appropriate solution that would imitate more accurately the ankle joint.

4 Simulations

Based on medical data from literature [5,6] a computer model for simulations was created. The model was done in MSC Adams software and anthropometric parameters were taken into account (figure 3).

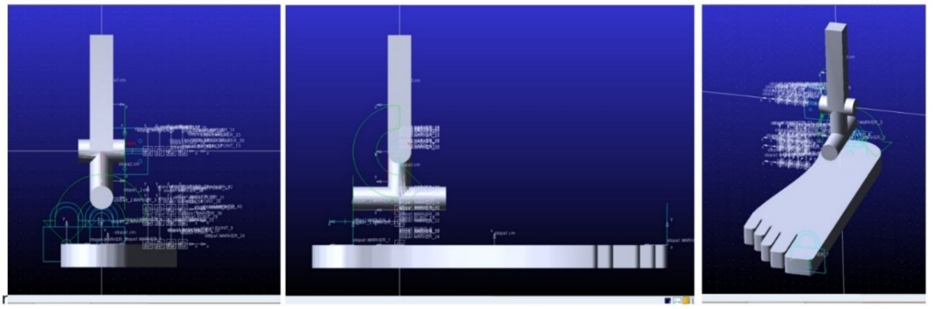

Fig. 3 Simulation model of the knee joint in MSC Adams software

Simulations were based on real gait data from recording a walking person using X-Sense motion tracking system. These simulations provided information on the X-length value dependent on joint position in relations to human body. The results are provided in figure 4.

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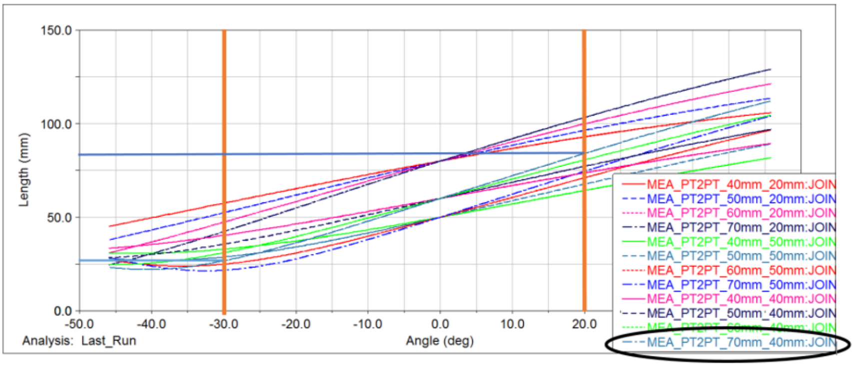

Fig. 4 The length compensation calculations – simulation results

Based on these results authors defined the most suitable position for the mechanical joint as well as length compensation value which was estimated to be 70mm.

5 Design of a mechanical ankle joint with length compensation

Based on these simulations laboratory tests were carried out that proved suitability of the solution. The designed system has length compensation that is dependent on angular position. The joint transfers load in the whole range of movement. The proposed joint is pending on patent (Polish Patent Office, call no. P.435022). The solution is presented in figure 5.

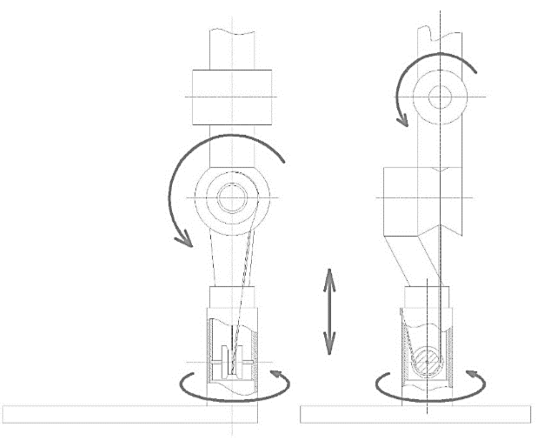

Fig. 5 The mechanical ankle joint (patent pending)

The joint consists of a guide sleeve which is connected with one end of the tension member. The tension member is guided by the first pulley (lower one in fig. 5) that is connected with the second element that moves in the sleeve. The second end of the tension member is connected with the second pulley (upper one in fig. 5). Flexion causes rotation of the second pulley and reeling of the tension member what effects in length change of the mechanism. The forces are transferred by the tension member.

In the above described solution, the elongation corresponds to the arch length of the reeled tension member in 1:2 ratio. To achieve 70mm compensation modifications are needed.

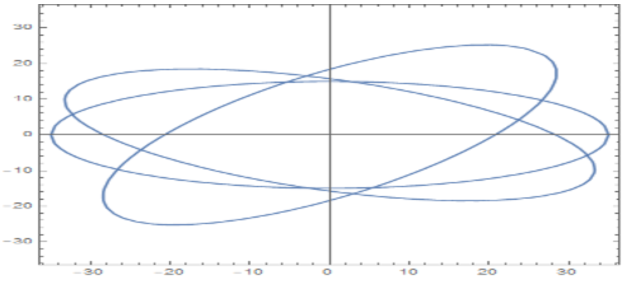

Fig.6 Ellipse rotation 30x70

The best results were obtained by using the second pulley in shape of an ellipse because tension member is not only reeled but also pulled by changing lever position (see fig. 6).
Calculation results for tension member length change of the 30mm x 70mm ellipse are depicted in figure 7.

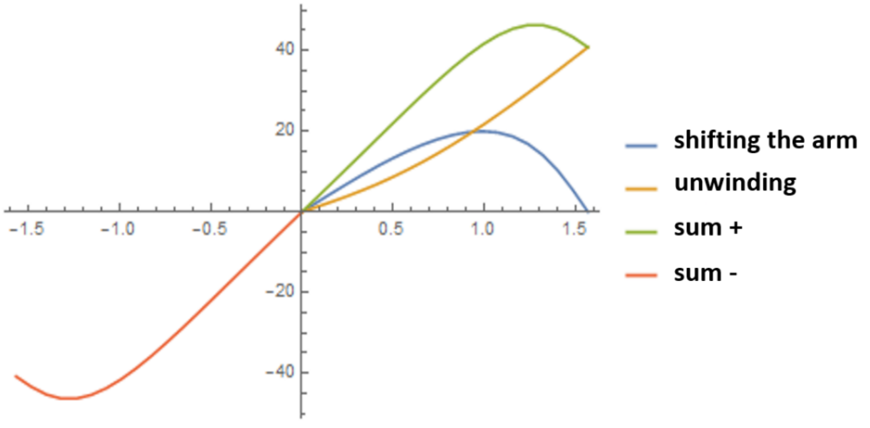

Fig. 7. Tension member length change due to ellipse rotation.

6 Conclusions

A properly designed exoskeleton must be comfortable for a user. The solution should minimally limit natural motions and provide load transfer all the time. To achieve this goal in the ankle joint the solution must contain a system for changing axis of rotation position. One of the proofed solutions is the one proposed by the authors. This patent pending design is not limited to the ankle joint but can be also applied in e.g. knee joint or upper limbs joints.

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