XPED’s Reality Check
An evaluation of how human and exoskeleton adapt to each other

Brando Maathuis
XPED’s reality check
An evaluation of how XPED and human adapt to each other

MASTER OF SCIENCE THESIS

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The contents of this thesis are confidential.

Author:
Brando Maathuis

Exam committee:
Prof. Frans C.T. van der Helm, PhD
Wietse van Dijk, MSc
Ir. Gerald Wisse

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Faculty of Mechanical Engineering · Delft University of Technology
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The research described in this thesis is part of a larger project on the XPED exoskeleton, which is funded by company X. This thesis is written at entry-level to be readable by a broad audience.

It is written to document the analysis I have done on XPED, a passive walk assisting exoskeleton. The aim of my project was to investigate why the current version of XPED is not able to achieve a decrease in energetic cost for normal walking. From this analysis, some results were specific for XPED, but also general problems were found that go for all exoskeletons.
This thesis presents research done on XPED, a passive walk assisting exoskeleton. It uses exotendons to assist the user, which are elastic elements running over multiple joints which are able to store and redistribute energy over these joints. A computer model predicts that joint powers of the user would decrease when walking with XPED, compared to walking without XPED. Because of these predictions a lower energy consumption for walking with XPED was expected. Previous research shows however that this is not the case, but that the energy consumption of the user increases when walking with XPED. The goal of this research was to find the reasons why XPED does not help the user decrease his energy consumption when walking. Possible mismatches between reality and model were identified and tested on occurrence. Three hypotheses were formulated:

A: The user alters his gait pattern

B: XPED’s hip harness deforms

C: XPED moves relative to the user

These effects do not occur in the model but they were thought to occur in reality. They all have the potential to decrease the amount of energy storage in the exotendons and thereby decrease the energy efficiency of XPED. Using motion capture measurements on three subjects, the kinematics of XPED as well as those of the human were measured. From these measurements, all three hypotheses were accepted.

A: The human alters his gait pattern due to the exotendons by walking on his toes more, thereby relaxing the exotendons. Changes in back orientation were also found. Two of three subjects bend over more, thereby relaxing the exotendons and one subject walked more upright, thereby stressing the exotendons more. The energy stored in the exotendon decreased due to these gait alterations ranging from 9.5 to 32.6 Joule.

B: The original hip harness of XPED was found to deform significantly due to the exotendon forces but the stiffening elements added to the hip harness brought down the energy loss from 6.7 Joule for XPED 2.1 to 2.3 Joule or lower for XPED 2.2.

C: It was also found that XPED moves relative to the user. The effect of these movements on the stored exotendon forces can range from 0 to 6.7 Joule for XPED 2.2, depending on how the user adapts to less relative movement.
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1 INTRODUCTION

1.1 Exoskeletons

Exoskeletons are either powered or unpowered devices that can be worn by a user and aim to assist the user in some way. These ways of assisting can be divided into two groups: acquiring new functions and enhancing functions. The main difference between these groups lie in how they are controlled, as will be explained in the following section.

1.1.1 Acquiring new functions

Exoskeletons can help patients to acquire functions that they do not have, such as walking or climbing stairs. The exoskeleton called the ReWalk \cite{1}, of which a picture is shown in Figure 1.1.1a, is an example of such an exoskeleton. It provides the user the ability to walk, even if he is not able to move his legs at all. This exoskeleton has robotic legs that move synchronous with the human legs. The exoskeletons hip, knee and ankle power their human equivalents resulting in a walking motion. Stabilization is done by the user with crutches.

Since the exoskeleton provides a new function to the user it has to detect the intentions of the user. By using buttons on a wrist console the user can put the device in different modes, such as walking or climbing stairs. With the use of motion sensors that register upper body movements the desired motion is initiated, continued or stopped.

\begin{figure}[h]
\begin{center}
\includegraphics[width=0.4\textwidth]{fig1a.png} \quad \includegraphics[width=0.4\textwidth]{fig1b.png}
\end{center}
\caption{Exoskeletons with different assisting purposes}
\end{figure}
1. Introduction

1.1.2 Enhancing functions

Enhancing functionality can range from increased strength and speed to increasing the energy efficiency of a certain task. BLEEX [2] is an exoskeleton that enhances the users functionality by offering load-bearing augmentation. A picture of this exoskeleton is shown in Figure 1.1.1b. The exoskeleton consists of two legs that are powered at the hip, knee and ankle. On these legs a backpack is mounted that houses the power supply and the extra load that it carries for the user. Because it enhances existing functionality it does not have to detect what the users intentions are but it has to follow the user. BLEEX is controlled by an inverse model that dictates the exoskeleton to move in concert with the user.

1.1.3 General difficulties

Two general difficulties that play a role in every exoskeleton are firstly the physical interface between the exoskeleton and the user and secondly that exoskeletons have to compensate for their adverse effects before the user is supported. If the exoskeleton has to move synchronous with the user a stiff connection is desired, which is hard to accomplish since human tissue is compliant. The demand that it has to be comfortable for the user also adds problems. A coupling is always a trade-off between comfortability and stiffness. Furthermore, exoskeletons in itself are never a goal, they are a means to achieve the goal of supporting the user. Exoskeletons always add mass to the user for which they have to compensate in terms of support before they actually support the user. Even though the support forces of an exoskeleton may help the user, if they do not outweigh the adverse effects of the added mass, the total exoskeleton will have a negative effect.

1.2 Walking and energy efficiency

1.2.1 Gait cycle

Walking is a cyclic movement that can be divided into repetitive steps. The trajectory that one leg follows during one step is called the gait cycle which by convention starts and stops at heel strike. An image illustrating the gait cycle is shown in Figure 1.2.1, where key points are depicted. The gait cycle can be divided into the stance phase, which lasts approximately 60% of the cycle, and a swing phase, lasting the remaining 40%.

1.2.2 Metabolic cost and energy efficiency

The metabolic cost is the amount of energy it takes a human to perform a certain task. This is largely determined by the sum of all his muscle activity. Muscles can only actively contract, not extend and the amount of energy they consume depends on their activation level which is controlled by electrical signals. The activation levels can
be measured using and ElectroMyoGraphy, also called EMG measurement, by placing electrodes on the skin over the muscle which can detect the energy voltage in the muscle.

If a muscle is activated, it will consume energy, whether it is providing negative or positive work. Negative work is provided when the muscle is elongated while being activated, since the direction of movement is opposite to the direction in which the muscle provides force. Positive work is provided when the muscle is shortened due to its contraction force.

If the metabolic cost for a certain task is decreased, the energy efficiency for that task is increased, since less energy is needed to reach a goal.

1.3 XPED

XPED is a passive exoskeleton that aims to increase the energy efficiency of normal walking for healthy humans with respect to normal walking without XPED [3]. Pictures of three different versions of this exoskeleton are shown in Figure 1.3.1. Since it is passive it uses no actuation whatsoever and the only means of supporting the user are the so called exotendons. How they function is explained in the next section.

The directly apparent goal of developing XPED is to build an exoskeleton which can be used by healthy humans to walk more energy efficient. This can be commercially exploited.

The other reason for developing XPED is the fundamental knowledge that is gained about the human gait, the way that humans react to certain support torques, con-
1. Introduction

Structuring exoskeletons and how to transfer forces or torques to a user. This knowledge can be used in exoskeletons that can help patients with too little muscle power walk again or walk for longer periods of time.

Pictures of different versions of XPED are shown in Figure 1.3.1. XPED is attached to the users pelvis using a hip harness and to the users feet with orthopaedic shoes. On these shoes and hip harness, connection points are made to which the leg segments of XPED can be attached. The lower leg segment of XPED is in the latest version also connected to the lower leg of the human using straps. The length of the leg segments of XPED can be adjusted to match their human equivalents. The connection point at the hip harness allows adjustment of the hip joint of XPED in the vertical direction. By adjusting the length of the back and front parts of the hip harness, the horizontal positioning of the hip joint can be tuned. The straps at the lower leg can be adjusted vertically from the front to the back such that the knee joint of XPED coincides with the human knee joint. This coinciding is approximate since the human knee does not act as a pure hinge joint. The alignment of XPED’s joints and the human joints are important since it will ensure maximum freedom of movement for the user.

Ab/adduction of the hip is freely possible for the human, as well as exo/endorotation of the hip and flexion/extension of the knee. The movements that are supported by the exotendons are flexion/extension of the hip and the ankle.

![XPED versions](image)

**Fig. 1.3.1:** Three versions of XPED. From left to right is each version an advancement of the previous.

1.3.1 Exotendons

Exotendons, also called artificial tendons, are elastic elements that can span multiple joints and that are able to store and redistribute energy over these joints. In the case
of XPED two exotendons are used (one for each leg) which consist of a dyneema cable running over the hip, knee and ankle joint. Each one is connected in series with a leaf spring positioned at the foot. These exotendons can assist the user when energy is absorbed by muscles.

Energy absorption by muscles happens for example at mid-stance, when the calf muscles are being activated to generate force, while being stretched. In a way these muscles are then applying a braking force. This energy absorption can be considered as wasting of energy. If well designed, an exotendon can be elongated along with the elongation of the muscle. Due to its elastic properties a force will be generated by the exotendon, thereby decreasing the 'braking' force required of the muscle.

By elongating the spring elastic energy is stored which can later be used to help muscles generate power. Continuing the example, just after the large amount of energy absorbed by the calf muscles at mid-stance, a large amount of energy has to be generated by the muscles at push-off. By relaxing the exotendons simultaneously they deliver a part of the force that the muscles would have to deliver.

Not only is it intuitive that helping the muscles by providing a part of their required force has an energetic advantage, this is also proven by research [4, 5]. It shows that appropriate torque applied to joints decreases the amount of torque that the muscles will generate.

The exotendons can be disengaged by disconnecting the cable from the spring. This is used in measurements to isolate the effects of the exotendons.

An illustrative analogy to the role of exotendons can be made by modern day electric cars, in which regenerative braking is used. Instead of mechanical brakes \{=muscles absorbing power\} that convert kinetic energy into heat that is subsequently dissipated into the surroundings, regenerative braking is done by the electric motors \{=exotendon\} that can also fulfil the role of generator. By braking with the motors kinetic energy is converted into electric energy that can be stored in the cars batteries \{=elastic part of exotendon\}. This energy can later be used again to accelerate the car using the same electric motors \{=exotendon\}.

### 1.4 Problem definition

The problem that this thesis deals with, was found during previous research [3]. This problem will be presented here along with the most important aspects of that research. A model was made of a user walking with XPED to optimize the exotendon parameters such as the moment arms of the exotendon at each joint, their slack length and their stiffness. They were optimized such that they minimized the effort of walking using the cost function given in Equation 1.1 (from: [3]).

$$ J = \sum_{i=\text{hip, knee, ankle}} \int_{t=0}^{T} |P_i(t)|dt. \quad (1.1) $$
With $P_i$ being the power at joint $i$, which is defined as the torque at that joint generated by the muscles times the angular velocity of that joint. The absolute power is taken, since absorbing power with muscles also cost energy, as explained in subsection 1.2.2. It was shown that metabolic cost increases linearly with mechanical work [6].

Simulations were done with this model and normal gait data as motion input. The simulations showed that a decrease of 29.9% in total joint power could be achieved. With this outcome a decrease in energy consumption for walking with XPED was expected. Despite these predictions, measurements have shown that wearing XPED without the exotendons will increase the metabolic cost of its user by 36%. Adding the exotendons yields a benefit of 2%.

This proves that the positive effects of the exotendons are not able to overcome the negative effects of the added weight of the exoskeleton. It also shows that a difference exists between the predictions of the model and the reality. Moreover, this proves that XPED does not reach its design goal. The general problem can thus be formulated as:

**XPED does not achieve a decrease in metabolic cost for normal walking**

The goal of this thesis is to answer the question why XPED does not achieve a decrease in metabolic cost. To achieve this goal, an analysis of XPED was done, during which possible problems were identified. Measurements were then performed to assess whether these possible problems occurred in reality and if so, how large the effects of these problems were.
In the previous chapter the problem is presented. In this chapter, the method is explained of finding out what the possible problem causes are, which of these causes occur and if they do, to what extend. By determining the latter, it is possible to assess how large the effects are of each occurring problem.

2.1 Analysis XPED

The problem presented in section 1.4 is that contrary to predictions done by simulations, XPED is not able to reduce the energy consumption for walking. So, if the reality was exactly the same as the model, an energy reduction would be achieved. To gain a deeper understanding of XPED, the nature and the effects of these differences was researched.

There are two sides to the mismatch between the reality and the model. It could be that too large or even erroneous simplifications are done on the model side or it could be that the human with exoskeleton behaves very different from what is assumed, resulting in a decrease in energy efficiency of XPED. This research focusses on the mismatches on the reality side while the model mismatches on the model side are investigated by a colleague student for his master thesis. The assumptions that are the foundation of the model are:

A: The movements of the human are not altered by the use of XPED.
B: XPED’s parts are infinitely stiff.
C: XPED does not move relative to the human.

During the previous research, it was also discovered that the forces in the exotendon are much lower than in the simulations. A peak force of 7.1 Newton per kilogram body-weight was simulated, compared to a measured peak force of 4.3 Newton per kilogram bodyweight. A graph showing the simulated exotendon forces versus those that are measured on XPED 1 is given in Figure 2.1.1.

These exotendons are the core of the exoskeleton since they are the elements that provide the support. The rest of the exoskeleton is the link to the human body, enabling the exotendons to act on the user. These lower exotendon forces can thus explain why the predictions are more positive than the reality.

The model predictions are based on joint power, which is defined as the moment at a joint times the angular velocity of that joint. The supporting moment at a particular joint is defined by the force in the exotendon times the offset to the joint at which it acts. These offsets are the same as in the model, so then the only factor influencing the
supporting joint moment is the exotendon force. Due to its importance and potential to quantify the problem, this difference in exotendon force was taken as a measure for the mismatch between the model and reality. Finding out why these exotendon forces are so much lower brought about the mismatches between the model and reality. Three possible problems that are hypothesized to cause the lower exotendon forces are discussed below.

![Artificial tendon force graph](image)

*Fig. 2.1.1: Measured exotendon forces from previous research (solid line) vs. simulated exotendon forces (dotted line). The forces are normalized to the users body weight and the shaded patch indicates the mean plus and minus one standard deviation. Source: [3]*

### 2.2 Hypotheses

The deflection of the spring is determined by the geometry of the exoskeleton and in combination with the spring stiffness it determines the exotendon force. The exotendon is connected at certain offsets from the ankle and hip joint, so the deflection of the leaf spring is determined by the orientations of the hip, upper leg, lower leg and foot of XPED. Three hypotheses were formulated, each based on a possible problem that could cause the low exotendon forces.
2. Method

2.2.1 Hypothesis A: Human alters gait pattern

As stated in the previous section, the model assumes that the human does not adapt his gait pattern to either the exoskeleton or to the support. In reality however, it could be that the user is restricted in some movements or that the human re-optimizes his gait to the new situation thereby changing the amount of energy stored in the exotendon. A division has been made of two different ways in which the human gait can be altered.

Hypothesis A.1: Human alters joint angle pattern

Hypothesis A1 is that the human changes his pattern of joint angles during gait, thereby partly relaxing the exotendons. This happens for example when the user lifts his heel from the ground earlier than normal in the gait cycle. This way, the angle measured from the leaf spring to the back side of the lower leg is decreased and as a result, the tension in the exotendon is also decreased. An illustrating figure hereof is given in Figure 2.2.1, where the normal situation is shown, as well as a situation where the user is walking on his toes.

Hypothesis A.2: Human alters back orientation

The exotendon also generates a moment about the hip, to help the user swing his leg forward. This moment acts on the upper leg of the human with respect to the back of the human. Hypothesis A2 is therefore that the user bends his back forward instead of keeping it straight which again results in partial relaxation of the exotendon and a lower amount of elastic energy stored in it.
2. Method

2.2.2 Hypothesis B: XPED’s hip harness deforms

In the model XPED is assumed to be rigid, which is justified in the case of the aluminium and carbon tubes for the legs, the aluminium triangle at the foot and for the steel attachment of this triangle to the shoe. It is justified since deformations will be concentrated at the weakest part of a structure, which in this case is the hip harness that is made from ABS plastic.

Hypothesis B is that significant deformations will occur in the hip harness causing lower forces and elastic energy storage in the exotendon. A figure illustrating the possibility of force loss in the exotendon due to deformations in the hip is given in Figure 2.2.2.

On high speed videos, deformations in the hip harness were clearly visible to the human eye. They occur between the hip triangle, on which the exotendon forces are exerted, and the back plate, which distributes these forces over the back of the human. The deformation that is observed is rotation of the hip triangle with respect to the back plate, caused by deformations in the hip harness connecting those points. Frames of these high speed videos illustrating these deformations are given in Figure 2.2.3. These deformations will relax the exotendon, causing the forces in it to be lower than calculated in the model.

Fig. 2.2.2: The effect of deformations in the hip harness. Left: normal situation, right: situation with deformed hip harness. The hip triangle is rotated with respect to the hip harness. It shows the user (black), the main parts of XPED (blue), the exotendon (purple), the relaxed position of the leaf spring as reference (red,dotted) and the position of the leaf spring in the respective configuration (red,solid)
Fig. 2.2.3: Video frame analysis of hip deformation. Four frames of high-speed video are shown, the upper two frames show a subject walking with XPED without the exotendons in effect, the bottom two show the subject walking with XPED and using the exotendons. The two leftmost pictures show the beginning of stance, where the exotendon (when used) is not yet tensioned. It is compared to the two rightmost frames of the end of the stance phase, where the exotendon (when used) is maximally tensioned. Rough angle measurements are added for illustrative purposes. The force in the exotendon rotates the hip triangle significantly with respect to the back plate.
2. Method

2.2.3 Hypothesis C: XPED moves relative to the user

Finally, the model is based on the assumption that there is no relative movement of the exoskeleton with respect to the user. This implies that the exoskeleton is rigidly connected to the user, has the same joint angles as the human and also that the joints of the human and XPED are perfectly aligned.

It is certain that the coupling between the human and the exoskeleton is not rigid, since XPED is attached to soft tissue of the human. The question remains however, to what extent the exoskeleton moves with respect to the human and what the effects are of those movements. Misalignment of the XPED joints with respect to the human also results in movement of XPED relative to its user.

Hypothesis C is therefore that the exotendon force is lower than simulated due to relative movements of XPED with respect to the human.

How these relative movements can cause problems is shown in Figure 2.2.4, where the normal situation is shown, as well as a situation with XPED moving relative to its user.

**Fig. 2.2.4:** The effect of relative movement. Left: normal situation, right: situation where XPED moves relative to the user. It shows the user (black), the main parts of XPED (blue), the exotendon (purple), the relaxed position of the leaf spring as reference (red,dotted) and the position of the leaf spring in the respective configuration (red,solid)
2. Method

2.3 Measurements

All hypotheses were tested by measuring the kinematics of the human and the exoskeleton. This was done using a motion capture system. The effect of the exotendon on the human muscle activation was measured using EMG. The first part of this section describes what was measured and it is followed by a part on how that was done.

2.3.1 Measurements for hypothesis A1: Human alters joint angle pattern

Joint angles were measured for both walking with and without the exotendons and they were compared to standard joint angles obtained from the database of Winter [7]. The joint angles were calculated from the measurements by subtracting the orientations of adjacent segments. The hip angle was calculated by subtracting the upper leg orientation from the back orientation, the knee angle by the lower leg minus the upper leg orientation and the ankle angle by the lower leg minus the foot orientation.

2.3.2 Measurements for hypothesis A.2: Human alters back orientation

Back orientations were measured for walking with and without the exotendon. By comparing them, the effect of the exotendons on the back orientation was obtained.

2.3.3 Measurements for hypothesis B: XPED’s hip harness deforms

The rotational deformation of the hip harness with respect to the back of the exoskeleton was calculated by subtracting the hip triangle orientation from the back orientation. To assess the effect of deformations in the hip harness on the exotendon force, the hip harness was stiffened and measurements were done with and without these elements.

A close-up of the hip harness is given in Figure 2.3.1. The hip triangle (part a. in the figure), on which the hip moment is applied by the exotendon can rotate with respect to the back plate (part b. in the figure) by deformations in the harness. The direction of the rotation is indicated by $\varphi$.

Since the stiffening needs to act in the direction of $\varphi$, an aluminium tube is bolted to the backplate as the base of the stiffening. To achieve a larger moment arm with respect to the back plate another tube is bolted to the back plate, perpendicular to the first one. They are connected with each other by steel plates bolted onto their front and back.
2. Method

Since almost all the forces are in the sagittal plane, a steel plate is used to connect the first tube to the connection point of the hip triangle to the hip harness. The plate is placed in the sagittal plane to load it in its stiffest way. Pictures of the hip harness before and after the additions are shown in Figure 2.3.2a and Figure 2.3.2b respectively. XPED with these stiffening elements is from here on referred to as XPED 2.2.

Fig. 2.3.2: XPED hip brace, without (a) and with (b) stiffening elements.

2.3.4 Measurements for hypothesis C: XPED moves relative to the user

To determine the relative movement of XPED to the user, the orientations of the upper and lower leg of the human were measured, as well as of XPED. The orientation of the lower leg of the human is compared to that of XPED and the same is done for the upper leg orientations. Relative movements of the shoe and hip harness of XPED with respect to the human were not determined due to a lack of reliable and available landmarks for these segments on the human when XPED was worn.

2.3.5 Measurement apparatus

Measurements are done with XPED 2.1 and XPED 2.2. The only difference between XPED 2.1 and 2.2 are the stiffening elements described in subsection 2.3.3 which are present on XPED 2.2 but not on XPED 2.1. A picture of XPED 2.2 is given in 1.3.1c.
2.3.6 Motion capture system: Visualeyez

To measure the movements of both the user and the exoskeleton the motion capture system Visualeyez was used, which has an accuracy of 0.7 mm RMS [8]. Motion capture is a technique that allows so-called markers to be tracked through 3D space. It works by a set of cameras that detect the markers from different angles. The positions of these cameras with respect to each other are known by calibration and therefore the position of the marker can be calculated by combining the images of the different cameras. Recording position data with a high enough frame rate yields the motion of the markers. At least 60 Hz is advised for measuring movement patterns during gait [9], measurements were done at 100 Hz.

Motion capture was chosen for its low level of hindrance to the user. No forces were applied to the user by the measurement system, apart from negligible inertia of the markers. The particular Visualeyez system was chosen for its active markers. The advantage of active markers is that they emit light in a designated sequence because of which they can be labelled by the system. A disadvantage of this method is that the markers need an energy source in the form of small batteries to emit light.

To measure the position and all orientations of a rigid body, three markers are needed, which have to form a triangle.
2. Method

2.3.7 Marker placement

A set of markers was determined to measure the information described in sections 2.3.1, to 2.3.4. This set is shown on someone wearing XPED 2.2 in Figure 2.3.3. The positions of the markers are indicated by orange circles. The letter c followed by three numbers denote a marker cluster. This is a set of three markers placed in a triangle on a flat metal plate, which allows to measure positions and orientations in all directions. Table 2.1 lists the used markers and their position on the human.

Tab. 2.1: Marker placement

<table>
<thead>
<tr>
<th>Marker number</th>
<th>Marker position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heel</td>
</tr>
<tr>
<td>2</td>
<td>Toes</td>
</tr>
<tr>
<td>3</td>
<td>Ankle</td>
</tr>
<tr>
<td>4</td>
<td>Lower leg XPED</td>
</tr>
<tr>
<td>5</td>
<td>Knee XPED</td>
</tr>
<tr>
<td>6</td>
<td>Upper leg XPED</td>
</tr>
<tr>
<td>7</td>
<td>Hip joint XPED</td>
</tr>
<tr>
<td>8</td>
<td>Landmark on hip triangle</td>
</tr>
<tr>
<td>9</td>
<td>Landmark on hip triangle</td>
</tr>
<tr>
<td>10</td>
<td>Landmark on hip triangle</td>
</tr>
<tr>
<td>c1-3</td>
<td>Upper leg human</td>
</tr>
<tr>
<td>c4-6</td>
<td>Lower leg human</td>
</tr>
<tr>
<td>c7-9</td>
<td>Back plate XPED</td>
</tr>
</tbody>
</table>

Tab. 2.2: Markers per segment

<table>
<thead>
<tr>
<th>Segment</th>
<th>Markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>1-2-3</td>
</tr>
<tr>
<td>Lower leg XPED</td>
<td>3-4-5</td>
</tr>
<tr>
<td>Upper leg XPED</td>
<td>5-6-7</td>
</tr>
<tr>
<td>Hip XPED</td>
<td>8-9-10</td>
</tr>
<tr>
<td>Back</td>
<td>c7-9</td>
</tr>
<tr>
<td>Lower leg human</td>
<td>c4-6</td>
</tr>
<tr>
<td>Upper leg human</td>
<td>c1-3</td>
</tr>
</tbody>
</table>

Fig. 2.3.3: Picture of a user with XPED 2.2. Marker placement is indicated by the orange circles.
The markers were grouped per segment as listed in Table 2.2. Markers 1, 2 and 3 form a triangle that is rigidly connected to the shoe, from which the foot orientation can be calculated. The lower and upper leg of XPED were measured by the triangles formed by markers 3, 4, 5 and 5, 6, 7 respectively. The hip triangle was spanned by markers 8, 9 and 10.

The orientation of the torso was measured by cluster c7-9, which was attached to the back plate of the XPED harness. Since this harness is strapped to the human, it was assumed that the orientation of the back plate represents the orientation of the human back as well.

The orientation of the humans lower leg was measured by marker cluster c4-6, which was attached to the human shin by an elastic band and tape. It was placed on the boniest part of the shin so that minimal movement of the cluster with respect to the lower leg was assured.

In a similar way, the humans upper legs orientation was measured, by placing cluster c1-3 on the upper leg of the human using an elastic band and tape.

2.3.8 EMG measurements

Besides these kinematic measurements, EMG measurements were done to assess how the human changes his muscle activation as reaction to the exotendons. The muscles that were measured were the gluteus maximus, biceps femoris, semitendinosus, gastrocnemius medialis, rectus femoris, vastus lateralis and tibialis anterior. The electrode placement was done according to the SENIAM guidelines [10].

2.4 Measurement protocols

Two sets of measurements were done with the motion capture system, the first one with test subject one and XPED version 2.1 and the second with subjects two and three with XPED versions 2.1 and 2.2. Furthermore EMG measurements were done on subject four walking with XPED 2.2.

All measurements were done at a constant walking speed of 4.5 km/h and during all measurements with exotendons, the exotendon force was measured. Measurements with and without the exotendons in effect are denoted by WE and NE respectively. Before all measurements, the subject was given several minutes to get used to walking with the exoskeleton on a treadmill, until they felt confident to walk at 4.5 km/h. The measurement protocols are discussed below.

2.4.1 Motion capture measurements

Both sets of measurements with the motion capture system were done on a treadmill to ensure that the subject stays within the view of the cameras.
2. Method

Tab. 2.3: Motion capture measurements

<table>
<thead>
<tr>
<th>Trial</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>XPED 2.1 Without exotendons</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>XPED 2.1 With exotendons</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>XPED 2.2 Without exotendons</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>XPED 2.2 With exotendons</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

After adjusting XPED for the subject, the subject stood still in an upright position while a static measurement of 5 seconds was done. This static measurement gives the zero position of all markers and all orientations are later calculated with respect to this position. Table 2.3 lists the measurements that are done with the motion capture system.

The first set measuring only XPED 2.1 was started with a ten minute walk with the tendons connected to the spring, to provide support for the user. The first part hereof was intended for the subject to get used to walking with the exoskeleton. Of these 10 minutes, the second half of the eighth and tenth minute were measured. These are the measurements of the exoskeleton with exotendon.

Subsequently, the exotendons were disconnected from the springs, so at this point, the subject only had the adverse effects of the exoskeletons weight and no support. These measurements were done as a reference to determine the effect of the exotendons. The subject again walks for ten minutes, of which the second half of the eighth and tenth minute were measured.

The second set measuring both XPED 2.1 and 2.2 was started with a 10 minute walk with XPED 2.2, without the exotendons, of which the second half of the fifth and tenth minute were measured.

Following these ten minutes, a similar walk but with exotendons was performed and again the second half of the fifth and tenth minute were measured. These two trials were then repeated.

Hereafter, the stiffening elements were removed and another five minute walk was done, of which the second half of the first and fifth minute were measured. This last trial was done to assess the difference in exotendon force due to the stiffening of the hip harness and therefore no measurements without the exotendon were performed.

2.4.2 EMG measurements

The subject started with a four minute walk wearing XPED 2.2, without exotendons. Hereafter, the subject walked with the exotendons for twelve minutes of which the first three were measured, as well as the seventh, tenth and twelfth. This was followed by a five minute walk without the exotendons to rule out the learning effect.
2. Method

2.4.3 Subject characteristics

The subject characteristics are listed in Table 2.4.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Length [m]</th>
<th>Mass [kg]</th>
<th>Age [years]</th>
<th>Gender</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>1.91</td>
<td>93</td>
<td>54</td>
<td>Male</td>
<td>Motion capture</td>
</tr>
<tr>
<td>Subject 2</td>
<td>1.83</td>
<td>83</td>
<td>22</td>
<td>Male</td>
<td>Motion capture</td>
</tr>
<tr>
<td>Subject 3</td>
<td>1.73</td>
<td>72</td>
<td>26</td>
<td>Female</td>
<td>Motion capture</td>
</tr>
<tr>
<td>Subject 4</td>
<td>1.80</td>
<td>63</td>
<td>28</td>
<td>Male</td>
<td>EMG</td>
</tr>
</tbody>
</table>

2.5 Data processing

The information obtained by the motion capture system is a matrix with x, y and z-positions for each marker and for every time frame. The position of these markers is measured with respect to a global coordinate system of which the positive x-direction was equal to the walking direction, parallel to the treadmill. The positive y-direction was defined perpendicular to the plane on which the subject walked and finally the positive z-direction was perpendicular to the xy plane forming a right hand coordinate system. In this global coordinate system when the subject is facing in the walking direction, the x-axis is roughly parallel to the hip axis of ab/adduction, the y-axis to the hip axis of exo/endorotation and the z-axis to flexion/extension. An example of measured information in the xy plane for a single time frame is given in Figure 2.5.1.

Using Matlab® scripts, this position information is transferred into motion, force and energy information that is used to quantify each problem. A description of the processing is given in this section.

Fig. 2.5.1: Example of position information of a single frame in the sagittal plane, obtained using motion capture. The dots are the data, the connecting lines are added for clarity.
2. Method

2.5.1 Calculating segment orientation and mean step

To obtain the static position to which all measurements were compared, the mean position of the static measurement was calculated by taking the mean positions of all markers over one second. All measured segments were defined by grouping positional information of the markers that were on the same segment as listed in Table 2.2. Hereafter, the orientation and translation of each of those segments with respect to the static measurement was calculated for every time frame. This is done by minimizing Equation 2.1 for $R$ and $t$ using Horn’s unit quaternion based method \[11\]. $A$ and $B$ are sets of $n$ points (markers) in 3d space, $R$ is a rotation matrix and $t$ a translation vector.

For $A$, the marker positions of the static measurement were taken and for $B$ the marker positions for time frame $t$ were taken. This was solved for each segment and all time frames yielding the rotation matrix and translation vector of each segment over time with respect to the static measurement.

$$
\sum_{i=1}^{n} |R A(i) + t - B(i)|^2 \tag{2.1}
$$

Since all joints on XPED are rotational joints the translations are not of interest and the focus is on the rotations of the segments. The rotation matrices were translated into the angle of interest with euler angles. The order of euler angles was chosen to be x-y-z, because this way the ab-adduction and exo-endorotation of the leg at the hip joint were roughly represented by the x and y angle respectively, lining up the z axis with joint angles of interest: flexion/extension of the hip knee and ankle joint.

To check the robustness of the results, a mean step was calculated. During the 30 second measurements, between 20 and 30 steps were recorded and a step detection function was written that determines the heel strike moment. This was done by comparing the velocity of the heel marker in the x-direction with the velocity of the treadmill belt. Heel strike occurred when these became equal, which research proved to be a reliable step detection method \[12\].

With the heel strike moments known, the orientations of the segments over time were cut into single steps. After equalizing the number of frames in each step by interpolating, the steps were summed and divided by the number of non-zero measurements. This way none of the zero measurements, which occur when a marker is lost during a frame, contributed to the mean step. The standard deviations over the steps for each time frame were also calculated.

Outliers in the data were removed by deleting orientations that were more than two standard deviations away from the mean of the orientation of that segment. All spikes that were removed by this method were visually checked to be maximally 3 frames (0.03 seconds) This indicates that these spikes had to be introduced by measurement errors since this is too fast to have been caused by the subject.

Also visually, the data was checked on ‘faulty’ steps by plotting the orientations of the
2. Method

segments for all steps a single figure. Single steps that were obviously different from the rest were considered faulty and were omitted in further data processing.

2.5.2 Quantification of measured problems

When the possible problems were measured, they had to be compared quantitatively. A universal measure was needed in which the effects can be expressed. Since all possible problems were identified on their potential to influence the exotendon force, the measured kinematic effects were calculated into their effect on exotendon force. The variables, their meaning and units used for this calculation are listed in Table 2.5.

\textbf{Tab. 2.5:} Used variables for quantification of results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Meaning</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TLU$</td>
<td>exoTendon Length Upper leg</td>
<td>[mm]</td>
</tr>
<tr>
<td>$TLL$</td>
<td>exoTendon Length Lower leg</td>
<td>[mm]</td>
</tr>
<tr>
<td>$CL$</td>
<td>exotendon Cable Length</td>
<td>[mm]</td>
</tr>
<tr>
<td>$TL$</td>
<td>Thigh Length</td>
<td>[mm]</td>
</tr>
<tr>
<td>$SL$</td>
<td>Shank Length</td>
<td>[mm]</td>
</tr>
<tr>
<td>$HL$</td>
<td>Hip-attachment Length</td>
<td>[mm]</td>
</tr>
<tr>
<td>$AL$</td>
<td>Angle-attachment Length</td>
<td>[mm]</td>
</tr>
<tr>
<td>$x$</td>
<td>Spring deflection</td>
<td>[mm]</td>
</tr>
<tr>
<td>$k$</td>
<td>Spring stiffness</td>
<td>[N/mm]</td>
</tr>
<tr>
<td>$TF$</td>
<td>exoTendon Force</td>
<td>[N]</td>
</tr>
<tr>
<td>$SF$</td>
<td>Spring Force</td>
<td>[N]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Angle between upper leg and hip triangle</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Angle between deflected spring position and lower leg</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Angle between relaxed spring position and lower leg</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Angle between exotendon and deflected spring position</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Rotational deformation leaf spring</td>
<td></td>
</tr>
</tbody>
</table>
The tensioning of the elastic element is determined by the geometry of the exoskeleton. To calculate this tension from the joint angles, XPED was divided into two triangles as shown in green in Figure 2.5.2. The upper triangle was defined by the thigh of XPED (TL), the distance from the hip joint to the attachment point of the exotendon (HL) and finally by the exotendon running from the attachment at the hip to the knee (TLU). The length of the thigh was known as well as the offset from the exotendon-hip attachment to the hip. Combining this information with the earlier calculated hip angle, the length of the exotendon from hip attachment to the knee was determined using the cosine rule:

\[
TLU = \sqrt{TL^2 + HL^2 - 2 \cdot TL \cdot HL \cos(\alpha)} \tag{2.2}
\]

The total exotendon cable length (CL) was known and therefore, by knowing \( TLU \), \( TLL \) was also known. This information was then used to calculate \( \beta \), which is the angle that the spring would make with the lower leg, when it is considered as a torsion spring at the ankle that is connected to the exotendon via a stiff beam. Again using the cosine rule, this yielded:

\[
\beta = \cos^{-1}\left(\frac{SL^2 + AL^2 - TLL^2}{2 \cdot AL \cdot SL}\right) \tag{2.3}
\]

By comparing the calculated spring angle \( \beta \) with the measured ankle angle \( \gamma \), the rotational deflection of the spring was obtained. The deflection of the spring \( (x) \) was calculated using the cosine rule and a triangle defined by two sides of length \( AL \) with the rotational deflection of the spring as angle between them. The third side is then the linear deflection of the spring and follows from:

\[
x = \sqrt{AL^2 + AL^2 - 2 \cdot AL \cdot AL \cos(\gamma - \beta)} \tag{2.4}
\]

The exotendon force was finally calculated by multiplying the deflection of the spring with the spring stiffness of 8.3 [N/mm], yielding the spring force \( (SF) \), and accounting for the angle between the exotendon and the leaf spring as shown in Equation 2.6.
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\[\delta = \cos^{-1}\left(\frac{AL^2 + TLL^2 - SL^2}{2 AL TLL}\right)\]  \hspace{1cm} (2.5)

\[TF = \frac{SF}{\sin(\delta)}\]  \hspace{1cm} (2.6)

This thus yielded the tendonforce over a gait cycle. Calculating this pattern for different hip and ankle angles as described in subsection 2.5.4, a visual comparison can be made of the effects of each problem. This can be used for comprehending changes, but in order to objectively compare them, unambiguous numbers were required. For this number, the energy stored in the spring was chosen, for which the equation is:

\[E_e = \frac{1}{2}k x^2\]  \hspace{1cm} (2.7)

With \(k\) being the spring stiffness and \(x\) the deflection of the spring. The latter was determined during the calculation of the exotendon force and also the spring stiffness is known.

2.5.3 Measurement error propagation

To be able to assess the accuracy of the above mentioned exotendon force calculations, the propagation of the measurement error was determined.

As stated in subsection 2.3.6, the accuracy of the measurement system is 0.7 mm. Using three markers with this accuracy, orientations of segments were determined. The larger the distance between the three markers, the smaller the effects of the measurement errors became. In this case, the segments measured with the marker clusters are the least accurate, since their markers had the smallest relative distance.

The hip angle was determined by the difference between XPED’s upper leg and back, the latter of which was measured by a marker cluster. The minimal distance between markers on the clusters was 40.0 mm. With a positional accuracy of 0.7 mm, the orientational accuracy was \(\tan^{-1}(\frac{0.7}{40}) = 1.0\) degrees. The distance between the hip joint and exotendon attachment point at the hip triangle was 76.5 mm. With a rotational accuracy of 1.0 degrees, this results in a positional accuracy of 1.3 mm of the exotendon attachment point at the hip. Combining this accuracy with an exotendon stiffness of 8.3 N/mm, finally yields an accuracy of 11.1 N. This was accurate enough for quantifying the problems.

2.5.4 Quantification conditions

*Exotendon forces and elastic energy if hypothesis A=true, B=true*

The hip angle for walking with the exotendons minus the deformations of the hip harness was taken as angle \(\alpha\) and the ankle angle for walking with the exotendons was taken as \(\gamma\). Since the hip angle was determined by the back and the upper leg orientation,
the altered back orientation was herewith also taken into account. This yielded the exotendon force and elastic energy when all the problems of hypothesis A and B occur in the degree in which they are measured.

**Exotendon forces and elastic energy if hypothesis A=true, B=false**

To determine the exotendon force and elastic energy if deformations would not occur in the hip harness, but the human would alter his gait, the same angles were used as before, except now the deformation of the hip harness was not subtracted from the hip angle. The ankle angle for walking with exotendons was again used as \( \gamma \).

**Exotendon forces and elastic energy if hypothesis A1=true, A2=false, B=false**

The difference in back orientation was added to the hip angle for walking with exotendons and this was used as \( \alpha \) for the case where deformations in the hip harness were zero and the human would not alter his back orientation. The ankle angle for walking with exotendons was again used as \( \gamma \).

**Exotendon forces and elastic energy if hypothesis A=false and B=false**

Finally the hip and ankle angles for walking without exotendons were used as \( \alpha \) and \( \gamma \) respectively. This yields the exotendon force and elastic energy that would be obtained if the hip harness would not deform and the human would not adapt his joint angles or back orientation. This is considered the ideal case.

**Exotendon forces and elastic energy if hypothesis C=false**

The effects of the relative movements are assessed separately, since it is impossible to tell what the influence of less relative movement would be. The human gait could change to be the same as that of XPED, or the movements of XPED could change to those now measured on the human. The reality most probably lies somewhere in between. Therefore a range can be given of the possible effects of the relative movements. This was done by calculating the exotendon force and elastic energy for the joint angles as measured on XPED and for the joint angles as measured on the human.

### 2.5.5 Statistical analysis

A significance level of 5% was taken, which was determined using unpaired t-tests. A distinction in calculating the significance was made between data obtained from a single measurement trial and data obtained from combining two measurement trials. In the first case, a collection of steps was be calculated which were compared using the ttest2 function in Matlab®. For example, subtracting the upper leg orientations from the lower leg orientations in one trial to obtain the knee angle was done for each step, since the upper leg movement for step \( n \) is coupled with the lower leg movement of step...
When data of two different measurements was combined from different trials, this cannot be done for each step. Doing so would imply that the data is coupled, however step n from trial 1 is not coupled to step n from trial 2. In these cases, the mean and standard deviations were calculated per trial, after which they can be combined to new data with a mean and standard deviation. Determining the significance for this data was done using the program G*power3 [13]. It calculates the statistical significance of found differences given two means, their respective standard deviations and sample numbers.
The results of each possibly occurring problem will be discussed in this chapter and at the end a comparison of the magnitude of all the problems is given. Where appropriate, a schematic figure is shown next to graphs of a user wearing XPED, with markers indicated by circles and marker clusters indicated by two circles close to each other. The green circles indicate the markers of which the information is used to create the neighbouring graph.

### 3.1 Hypothesis A: Human alters gait pattern

**Fig. 3.1.1: Altered joint angles**

In Figure 3.1.1 a representative comparison between normal walking, walking with XPED 2.1 without exotendons and walking with XPED 2.1 and the exotendons for a single subject wearing XPED 2.1 is shown.

As can be seen for the hip and knee, both with and without the exotendons attached, the angles are quite similar to the normal gait data. For the ankle however, there are...
3. Results

noticeable differences. Table 3.1 lists the maximum ankle angles along with their standard deviations and the significance of their difference with the normal data. It is shown that for all three subjects for the case with the exoskeleton without the exotendons the peak height at the end of the stance phase is not significantly different from the normal data since $p > 0.05$. Under the influence of the exotendon, all three subjects significantly decreased the maximum angle of their ankle since $p < 0.05$.

Tab. 3.1: Maximum ankle angle and the significance of their differences with normal gait data, difference is significant when $p < 0.05$. NE means No Exotendons, WE means With Exotendons.

<table>
<thead>
<tr>
<th>Subject and trial</th>
<th>Max. ankle angle [degrees]</th>
<th>Sample size</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal walking, Winter</td>
<td>9.6 ± 4.8</td>
<td>19</td>
<td>-</td>
</tr>
<tr>
<td>Subj. 1, XPED 2.1, NE</td>
<td>6.6 ± 1.1</td>
<td>25</td>
<td>0.20</td>
</tr>
<tr>
<td>Subj. 1, XPED 2.1, WE</td>
<td>0.7 ± 0.6</td>
<td>25</td>
<td>0.00</td>
</tr>
<tr>
<td>Subj. 2, XPED 2.2, NE</td>
<td>8.9 ± 1.7</td>
<td>24</td>
<td>0.90</td>
</tr>
<tr>
<td>Subj. 2, XPED 2.2, WE</td>
<td>0.6 ± 1.0</td>
<td>24</td>
<td>0.00</td>
</tr>
<tr>
<td>Subj. 3, XPED 2.2, NE</td>
<td>13.3 ± 0.9</td>
<td>25</td>
<td>0.07</td>
</tr>
<tr>
<td>Subj. 3, XPED 2.2, WE</td>
<td>-2.5 ± 1.1</td>
<td>25</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The other possibly occurring problem of an altered gait is that the user can walk with a bend torso. This is measured by the orientation of the back of the exoskeleton. Walking with the exotendons is compared to walking without the exotendons. A graph comparing these two orientations for a single subject over 24 steps is given in 3.1.2a. The maximum differences between walking with and without exotendon are listed for all three subjects in Table 3.2 All found differences between walking with and without exotendon were significant with $p < 0.05$.

Tab. 3.2: Difference in back orientations between walking with and without exotendons.

<table>
<thead>
<tr>
<th>Subject and trial</th>
<th>Back orientation difference [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj.1, XPED 2.1</td>
<td>-2.4 ± 1.2</td>
</tr>
<tr>
<td>Subj.2, XPED 2.2</td>
<td>4.9 ± 1.7</td>
</tr>
<tr>
<td>Subj.3, XPED 2.2</td>
<td>7.6 ± 2.5</td>
</tr>
</tbody>
</table>
3. Results

(a) Comparison of back orientation for single subject walking with XPED 2.2 without tendons (Blue), walking with XPED and tendons (Red). Higher numbers for orientation mean that the subject is walking more bend over. The coloured patch indicates the mean plus and minus one standard deviation over 24 steps.

(b) Markers used for 3.1.2a shown in green.

Fig. 3.1.2: Altered back orientation
3. Results

3.2 Hypothesis B: XPED’s hip harness deforms

The measured deformations between hip triangle and back plate for a single subject walking with XPED 2.1 are given in Figure 3.2.1 and for a subject walking with XPED 2.2 in Figure 3.2.2.

Table 3.3 lists the maximum difference in deformation between walking with and without exotendons for each subject. The differences in exotendon force between XPED 2.1 and XPED 2.2 due to these deformations are listed in Table 3.4. The differences between XPED 2.1 and 2.2 are significant with $p < 0.05$.

(a) Rotational deformation of hip triangle with respect to back plate for single subject walking with XPED 2.1 without exotendons (Blue), with exotendons (Red). The coloured patch indicates the mean plus and minus one standard deviation over 25 steps.

(b) Markers used for 3.2.1a shown in green.

Fig. 3.2.1: Deformation of XPED 2.1

Tab. 3.3: Deformation difference of hip harness between walking with and without exotendons

<table>
<thead>
<tr>
<th>Subject and trial</th>
<th>Deformation difference [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj.1, XPED 2.1</td>
<td>15.5 ± 1.4</td>
</tr>
<tr>
<td>Subj.2, XPED 2.2</td>
<td>3.9 ± 0.6</td>
</tr>
<tr>
<td>Subj.3, XPED 2.2</td>
<td>1.7 ± 1.2</td>
</tr>
</tbody>
</table>
3. Results

(a) Rotational deformation of hip triangle with respect to back plate for single subject walking with XPED 2.2 without exotendons (Blue), with exotendons (Red). The coloured patch indicates the mean plus and minus one standard deviation over 24 steps.

**Fig. 3.2.2**: Deformation of XPED 2.2

(b) Markers used for 3.2.2a shown in green.

**Tab. 3.4**: Difference in exotendon forces between XPED 2.1 and 2.2.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Max. force XPED 2.1 [N]</th>
<th>Max. force XPED 2.2 [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj.2</td>
<td>122.6 ± 4.6</td>
<td>197.4 ± 8.1</td>
</tr>
<tr>
<td>Subj.3</td>
<td>150.2 ± 8.1</td>
<td>206.3 ± 9.8</td>
</tr>
</tbody>
</table>
3. Results

3.3 Hypothesis C: XPED moves relative to the user

Figure 3.3.1a shows the orientations of the lower leg of the user and of XPED. The background shading indicates where the differences the leg orientations are significant. Figure 3.3.2a shows the same information for the lower leg. The maximum differences are listed in Table 3.5.

(a) Orientation of human (black) and XPED (blue) upper leg for a single subject walking with XPED 2.2 with exotendons. Shaded background indicates a significant difference and the coloured patch indicates the mean plus and minus one standard deviation over 25 steps.

(b) Markers used for 3.3.1a shown in green.

Fig. 3.3.1: Orientations of upper leg of human and XPED.
3. Results

(a) Orientation of human (black) and XPED (blue) lower leg for a single subject walking with XPED 2.2 with exotendons. Shaded background indicates a significant difference and the coloured patch indicates the mean plus and minus one standard deviation over 25 steps.

(b) Markers used for 3.3.2a shown in green.

Fig. 3.3.2: Orientation of lower legs of human and XPED.

Tab. 3.5: Maximum difference in leg orientation between human and XPED per step. NE means No Exotendons, WE means With Exotendons. The gap in the data is due to a broken marker on the upper leg of subject 2.

<table>
<thead>
<tr>
<th>Subject and trial</th>
<th>Upper leg [degrees]</th>
<th>Lower leg [degrees]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj.1, XPED 2.1, NE</td>
<td>3.0 ± 2.5</td>
<td>7.7 ± 5.0</td>
</tr>
<tr>
<td>Subj.1, XPED 2.1, WE</td>
<td>9.2 ± 3.8</td>
<td>7.5 ± 3.6</td>
</tr>
<tr>
<td>Subj.2, XPED 2.2, NE</td>
<td>-</td>
<td>3.9 ± 3.8</td>
</tr>
<tr>
<td>Subj.2, XPED 2.2, WE</td>
<td>-</td>
<td>6.4 ± 1.5</td>
</tr>
<tr>
<td>Subj.3, XPED 2.2, NE</td>
<td>8.1 ± 2.0</td>
<td>6.4 ± 2.9</td>
</tr>
<tr>
<td>Subj.3, XPED 2.2, WE</td>
<td>10.9 ± 2.9</td>
<td>7.3 ± 4.1</td>
</tr>
</tbody>
</table>
3. Results

3.4 Quantification of results

The altered gait and the deformations of the hip harness are calculated into their effect on the exotendon force. Graphs showing the accumulated exotendon forces for XPED 2.1 and XPED 2.2 are shown in Figure 3.4.1 and Figure 3.4.2 respectively.

A bar diagram of the effects of these problems on the elastic energy stored in the exotendon is given in Figure 3.4.3 and their respective values are listed in Table 3.6. The obtained differences in exotendon force and elastic energy are significant since they are based on kinematic differences that were proven to be significant in the previous sections.

Table 3.7 lists the elastic energy stored in the exotendon for the gait pattern of XPED and for the gait pattern of the human. For this calculation the orientations of the upper and lower leg of XPED and the human are used, so the effects of the altered gait is also present in these numbers, the effects of deformations in the hip harness are not.

Fig. 3.4.1: Accumulated exotendon force for single subject over a gait cycle for different problems. No problems (cyan), if only joint angles change (red) if also back orientation changes (green) if also deformation of hip harness occurs (blue). Forces with normal gait data (purple).
3. Results

**Fig. 3.4.2:** Accumulated exotendon force for single subject over a gait cycle for different problems. No problems (cyan), if only joint angles change (red) if also back orientation changes (green) if also deformation of hip harness occurs (blue). Forces with normal gait data (purple).

**Tab. 3.6:** Elastic energy loss in exotendon for gait alterations and deformations.

<table>
<thead>
<tr>
<th>Subject and trial</th>
<th>Altered joint angles [J]</th>
<th>Altered back orientation [J]</th>
<th>Deformations [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub.1, XPED 2.1</td>
<td>11.3</td>
<td>-1.8</td>
<td>6.7</td>
</tr>
<tr>
<td>Sub.2, XPED 2.2</td>
<td>19.1</td>
<td>1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Sub.3, XPED 2.2</td>
<td>29.5</td>
<td>3.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Tab. 3.7:** Amount of elastic energy stored in exotendon for XPED and human gait pattern. The difference is the maximum loss in elastic energy due to relative movement. There is no data for subject 2 due to a broken marker on his upper leg.

<table>
<thead>
<tr>
<th>Subject and trial</th>
<th>XPED gait pattern [J]</th>
<th>Human gait pattern [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subj. 1, XPED 2.1</td>
<td>14.2</td>
<td>29.7</td>
</tr>
<tr>
<td>Subj. 3, XPED 2.1</td>
<td>10.3</td>
<td>17.0</td>
</tr>
<tr>
<td>Subj. 3, XPED 2.2</td>
<td>6.8</td>
<td>13.5</td>
</tr>
</tbody>
</table>
3. Results

Fig. 3.4.3: Accumulative elastic energy stored in the exotendon for different problems. No problems (cyan), if only joint angles change (red) if also back orientation changes (green) if also deformation of hip harness occurs (blue). Forces with normal gait data (purple). Altered back orientation of subject 1 is negative, hence the overlap.
3. Results

3.5 EMG measurements

The EMG measurements over a gait cycle are shown in Figure 3.5.1. The normalized maximum attained muscle activation levels are plotted in a bar diagram in Figure 3.5.2.

Fig. 3.5.1: EMG measurements of a single test for first walk without exotendons (red), with exotendons (green) and second walk without exotendons (blue). The coloured patches indicate the mean plus and minus one standard deviation over 15 steps.
Fig. 3.5.2: Bar plot of EMG measurements of a single test for first walk without exotendons (red), with exotendons (green) and second walk without exotendons (blue). Data is normalized for each muscle to the first trial and mean plus and minus one standard deviation are shown with errorbars.
4 DISCUSSION

4.1 Hypothesis A: Human alters gait pattern

In Figure 3.1.1 it is shown that wearing XPED has the largest effect on the ankle joint. Almost over the entire gait cycle the ankle angle for walking with exotendons is lower that normal, indicating that the user is walking on his toes. The peak height of the ankle is important since it partly determines how much elastic energy is stored in the spring.

Table 3.1 lists these maximum ankle angles. When the exotendons were in effect, all subjects showed a significant decrease in ankle angle compared to normal gait. The effect of the altered joint angles is by far the largest problem in terms of elastic energy Table 3.6.

Figure 3.1.2 shows that with the exotendons in effect, subjects two and three walked more bend over and that their back orientation is less constant. A surprising result is found for subject 1. For the latter, an almost constant difference of minus 2 degrees is found, showing that he walked more upright with the springs.

This could be caused by the Hawthorne effect [14], which causes the subject to intentionally or unintentionally affect the measurements because they are aware of being part of an experiment. Subject 1 is a physiotherapist and therefore most likely more aware of his gait pattern, especially when knowing that measurements are being performed. It could therefore be that he is overcompensating for being pulled forward. To what extend this is an exception should be investigated by performing gait analyses on more subjects.

The differences in joint angles between normal walking and walking with XPED without exotendons were not significant. This confirms that the construction of XPED offers enough movement freedom and that its hindrance to the user is kept to a negligible amount.

4.2 Hypothesis B: XPED’s hip harness deforms

The deformations are expressed relative to the static measurement. Therefore, if they were rigidly connected this difference would be zero. Without the exotendons, deformations in the hip harness also occur due to the human moving his legs back and forth and moving his torso during the gait. These deformations however are small compared to the deformations that are the effect of the exotendons acting on the hip triangle.

With Figure 3.2.1 and 3.2.2, the added value of the stiffening elements is shown, since the deformations are significantly less in XPED 2.2 compared to XPED 2.1. Table 3.3 lists the maximum difference in deformation between walking with and without exoten-
dons for each subject, where the large differences between XPED 2.1 and 2.2 are quantified. Deformations still occur in the hip brace due to movements of the human inside it. The effects hereof are small however compared to the total amount of elastic energy stored in the exotendon.

From Table 3.6, it can be seen that the loss in elastic energy due to the deformations is less for XPED 2.2. The loss due to the altered gait however increase. This data shows that stiffening the hip harness leads to higher forces in the exotendon which in turn lead to larger alterations of the gait pattern.

4.3 **Hypothesis C: XPED moves relative to the user**

It is proven that significant movement of XPED relative to the user occurs. This goes mainly for the upper leg which was expected since the lower leg of the human is strapped to XPED. As stated in section 2.5.4, the effect of bringing down this relative movement is not fully predictable. This depends on what changes with less relative movement, the user moving more like XPED does now or XPED moving more like the user does now.

Table 3.7 lists the elastic energy stored in the exotendon for the gait pattern of XPED and for the gait pattern of the human. If the the user changes his gait to coincide with XPED, the elastic energy in the ‘XPED gait pattern’ column will be obtained, whereas if the motion of the user stays the same and XPED would follow the user, the elastic energy in the column ‘Human gait pattern’ is obtained. The reality will most probably lie somewhere in between.

4.4 **EMG Measurements**

All subjects stated that walking without the exotendons after having walked with exotendons felt as if they were missing support. All 5 subjects stated this at own initiative, so without a preceding question, adding to the credibility of this difference. Different descriptions were given of how this was noticed. It felt as if their feet felt heavier, they missed a ‘push’ at their heel at push-off, as if their torso was pulled back or as if they were walking with bend knees.

From these observations, it was expected to find a noticeable effect hereof in the EMG measurements. As can be seen in Figure 3.5.2 that apart from a large difference at the rectus femoris the maximum activation levels are very much alike for the different trials. The large difference that is found is most likely some kind of measurement artefact, since it is found in a single muscle and it only appears in the first measurement trial. If it was a real difference it would also have to show up in the third trial, since the first and third trial have the same conditions.
Although the muscle activation does not change, the movements of the human can change resulting from the exotendon forces. This way differences in gait pattern can be noticed by subjects while it is not measured in EMG.
4. Discussion
5 CONCLUSION

5.1 Hypothesis A: Human alters gait pattern

The most important finding of this research is that the user adapts his gait to the support. All subjects showed the adaptation of lifting their heel earlier in the gait cycle. Two of the three subjects walked slightly bend over. The gait alterations were responsible for 9.5 to 32.6 Joule decrease in energy storage in the exotendons. It is striking that these adaptations are not aimed at making optimal use of XPED, but rather at avoiding tensioning the exotendon, therewith nullifying the use of the exoskeleton. This was confirmed by the EMG measurements. Exoskeleton designers should be aware of this adaptation and put effort in investigating how this affects their support principles. This is especially important for passive exoskeletons, since the user itself has to store energy in the exoskeleton, enabling him to decrease this storage of energy.

5.2 Hypothesis B: XPED’s hip harness deforms

Deformations of the original hip brace also proved to have a large negative influence on the amount of elastic energy stored. By the addition of the stiffening elements, the loss in elastic energy due to deformations is decreased from 6.7 Joule to 2.3 Joule or less and the force in the exotendon increased significantly with 37% or more.

5.3 Hypothesis C: XPED moves relative to the user

Finally the coupling between human and XPED is proven not to be a rigid one. Movements occur with respect to each other, up to 10.9 degrees for the upper leg and 7.7 degrees for the lower leg, resulting in an upper bound of 15.5 Joule energy loss for XPED 2.1 and 6.7 Joule for XPED 2.2. Combining the EMG measurements with the altered gait pattern leads to the conclusion that the human does not alter his muscle activation pattern and that the joint angles are altered due to the forces of the exotendon. Part of the philosophy of the exotendons is that the human calf muscle activation can decrease, since the tensioning of the exotendon provides part of the braking force while simultaneously storing energy in the exotendon. If the human does not decrease his calf muscle activation, the normal braking force of the calf muscle is provided, as well as a braking force of the exotendons. This will lead to lower ankle angles, less energy stored in the exotendon and no change in EMG signals, which is all proven to happen in this research.
5.4 Future directions

Two recommendations arise from the gait pattern measurements. The first one is that these measurements should be performed on a larger group of subjects. It is shown that altering the gait pattern has the potential to have a large effect, now the generality of these findings should be determined.

The second recommendation is that users should be trained to make maximum use of XPED, since users now adjust their gait pattern to relax the spring, rather than to stress it. This should be done by instructing the users to keep their heel on the ground longer and training them by giving feedback on the achieved exotendon force.

The recommendation following from the measurements on the relative movement is that straps should be added connecting the upper leg of XPED with the upper leg of the human and measurements should be done with and without these straps. This way the effects of less relative movement can be assessed.
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