RIJKSUNIVERSITEIT GRONINGEN

Are Intelligent leg prostheses better than conventional leg prostheses?

Thesis - Prostheses

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Abstract

In this thesis it is investigated whether Intelligent leg prostheses are better than conventional leg prostheses. In the 1990s the Intelligent prostheses were developed. Nowadays the intelligent prostheses conquer the prosthetic market. Intelligent Prostheses are said to be the future. But are they really? The main question is answered trough a few paragraphs. Advantages and disadvantages of intelligent prostheses (IP) in literature are examined.

Disadvantages of the IP are almost not found in literature, while advantages are numerously found. From comparison studies between intelligent prostheses and conventional prostheses it appeared that intelligent prostheses have a lot of advantages. They can improve gait and balance, show less oxygen consumption, and you're able to walk down/ up stairs and ramps. Also the users preferences go to the intelligent leg. Negative points to the intelligent leg prosthesis aren't really there, or at least not in literature. However the intelligent prosthesis is not found to be less cognitive demanding as said in comparison to mechanical prostheses. It is also presumably that the intelligent prosthesis are much more expensive than the mechanical ones.

Altogether you can see there are a lot of advantages towards Intelligent leg prostheses compared to conventional prostheses. The conclusion of this thesis is that the Intelligent Prostheses are indeed better than conventional prostheses. And will probably be even better in the future.

Index

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Introduction

Imagine a woman walking down the street, she is walking a bit strange. Stumbling, moving her upper body constant a bit more to the right than left. Most people would think she sprained her ankle or something like that, but nothing else. However, if you look closer you can see she has an artificial limb. Most of the people react really shocked if they see something like this, because they didn't expect it. However prostheses will become more and more normal in the future. They'll work even more like a normal intact leg.

Artificial limbs are nowadays so well developed, even further than what most people think. From the oh so known wooden leg of the pirate, the wooden toe of a Egyptian, to a leg of steel, or even of plastic with the appearance of a real leg, and ultimately to the so called Intelligent Prosthesis.

The last one will be discussed in this thesis. Designers say the Intelligent Prosthesis is the future. But is it really? Is an intelligent prosthesis in comparison to conventional prosthesis really better? What are the benefits of intelligent Prostheses in comparison to conventional prostheses? In this thesis I will lead you trough all the prostheses that are already in the market, the history of (leg)prostheses until the intelligent prostheses. At the end of this thesis I hope I have answered the questions about Intelligent Prostheses trough a few paragraphs. I hope you will enjoy reading my thesis.

Prostheses

Prosthesis, or prosthetic limb, is a device that substitutes a missing or defective part of the body. [1] The prosthesis is custom-made device, which helps you to restore the original function of the missing part. In this thesis, only the leg prostheses are examined. There are different leg prostheses on the market; below-knee prosthetic, above-knee prosthetic and the ankle prosthetic. Which prosthesis is needed, depends on the level op amputation.

History prosthesis

Prostheses have been developed for over many years. The road to the intelligent leg from now, began about 1500 B.C. Proof of the first prosthesis is from the time of ancient Egypt. A wooden toe was found in the Theban Necropolis, Egypt. [2] It is believed that the Egyptians wore the prostheses more for a sense of 'wholeness' than function. However this prosthesis appears to have been functional, because the toe is necessary for balance.[3]

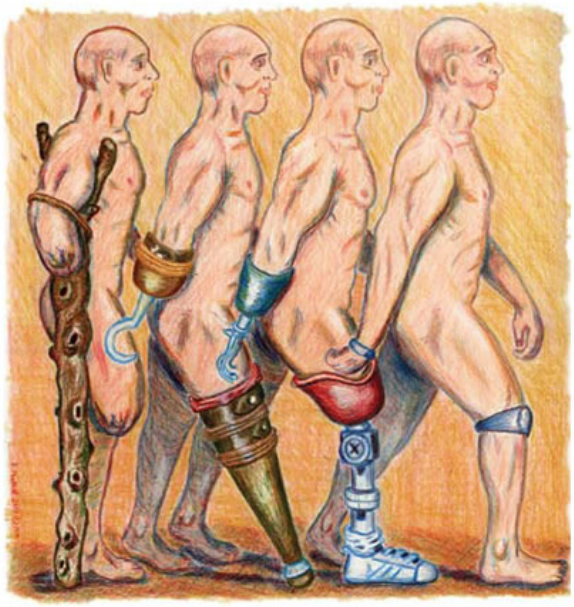

Figure 1: Developments in the leg prosthesis

The first written reference to a (leg) prosthesis was around 500 B.C. by Herodotus. He wrote about a Persian prisoner who escaped from his chains by cutting off his foot, which he later replaced with a wooden substitute. [4]

In the early Middle Ages (476 to 1000) the peg leg was introduced. Most of the prostheses were used for cosmetic purposes, to hide malformations or injuries from battle. The peg leg that was more 'usable' for daily functions, were only accessible by rich citizens. The peg leg was very simple and was most used for wounded soldiers. The prosthesis was static and wasn't really usable to walk on. [5]

During the Renaissance (1400s to 1800s) the prosthetics were fully in development. The prostheses were made of different materials; iron, steel, copper and wood. In the 1500s, prosthetics became more functional in use.

Around 1540 Lorrain, a French locksmith, used when making prostheses, glue, paper and leather instead of heavy iron. This was an important contribution to the prosthetic field. Because it makes the prosthesis much lighter. And with it, of course easier to walk on. [3]

In 1696 Pieter Verduyn published his paper: ''*Dissertation epistolaris de nova artuum decur tandorum ratione*.'' In this paper he wrote about his new prosthesis. He developed the first non-locking prosthesis for below the knee. This prosthesis is seen by many as the basic of current prostheses. [6]

In the Civil War of America (1861-1865) the amount of amputations rose enormously. Veterans were dissatisfied with the lach of technology in the prosthetics. This ensured that for the first time state governments payed for prosthetic devices for war veterans. [3] This gave a huge boost to the

prosthetic field. In 1863, Dubois Parmlee developed a prosthesis with a suction socket. This design also had an multi-articulated foot and polycentric knee. [7]

As time progressed new developments were made in the prostheses. In 1912 the first aluminium leg prosthesis was made. During the World War II, a suction socket for above-knee prosthesis was invented, which was a major advancement in the attachment of lower limbs [8]. In 1950s Electrically and pneumatically powered devices appeared for general use.

In 1990s a microprocessor in an external prosthesis was used for the first time. This was a great invention for further developments in the area of prosthetics.

In the 21st century, which seems to be the biggest improvement, the so called Intelligent Prostheses were invented. With the use of microprocessors and hydraulic systems in these prostheses, it seems it's becoming easier to walk. Prior to the intelligent prosthesis, amputees weren't able to walk well on irregular surfaces or walking down or up the stairs. They would stumble or had to walk with a stiff leg. These new leg prostheses are 'intelligent', you can say the prostheses can think for themselves. The first intelligent leg was already on the market in 1997, it was called the C-leg. More designs followed: Ossür's POWER KNEE, PROPIO FOOT and the RHEO KNEE. The developments in de 21th century followed one another quickly. And probably will continue through the years. [9]

From Conventional prostheses to Intelligent prostheses

As you could see, the developments were enormous. The last development, from conventional to intelligent prostheses, is frequently studied. The intelligent prosthesis is said to be better, however the conventional prosthesis is still much in use.

Before the intelligent prostheses are discussed, it is necessary to know a bit about walking. Walking can be divided in 2 different phases. First there is the swing phase, this is the phase where the leg moves along the other leg. Second there is the stance phase, where shock is absorbed followed by the actual support of the leg and ended by the deposition of the foot. The swing phase is important for creating a natural gait. Here for the knee needs to be bended, or else you will fall over your own feet.

A problem with the conventional prosthetic leg is the lack of 'feeling.' You don't feel the position of the leg, which can cause an unnatural gait. Also walking on stairs can cause stumbling. With the newest development, intelligent prostheses, it is said that a more natural walk can be performed. With the intelligent leg you can 'feel' were your leg is and the leg automatically adapts itself to your walking condition.

In 1997 Otto Bock Orthopedic Industry introduced the first Intelligent Prosthesis on the market, the C-leg. An intelligent prosthesis, for example an intelligent knee, is a self-regulated robotic system. This prosthesis, focused on leg-prostheses, learns to take the right settings that are needed for varying walking speeds.

An Intelligent Prosthesis is microprocessor-controlled, which includes a pneumatic and hydraulic control in one electronic unit. The pneumatic control serves for the appropriate shin (tibia) swing time and the hydraulic control works during the stance phase of the gait.

A computer in the knee responds to the inputs: time, angle and force sensors. This computer than triggers the electronic unit. The microprocessor response by selecting the right settings for stability and speed. [10] For better understanding, you can think of walking. Walking, followed by an acceleration. To be able to accelerate, the leg must be faster in time and also the forces will increase. The microprocessor will react by changing its settings. Next, you are able to accelerate. If the settings wouldn’t change, you would fall down.

Which Intelligent Prosthesis are there?

Over the last 10 years a lot of progress has been made in the intelligent prostheses. The companies Otto Bock and Ossür really own the marked in this area. Some of the most known and used intelligent prostheses are outlined below.

Otto Bock C-leg:

Thus in 1997 Otto Bock Orthopedic Industry introduced the C-leg. With this prosthesis, adaptation to the individual gait pattern was made possible.

Until then, the prostheses that were already on the market, weren't really suitable for the user's active pursuits such as climbing stairs or cycling. With the advent of intelligent prostheses this all changed. The intelligent prostheses can detect the walking phase of the user; Is he/she walking, running, climbing stairs or cycling. After detecting, the leg adjusts accordingly in real time.

Figure 2: C-leg

The C-leg contains hydraulic cylinders which control the flexing of the knee. There are different sensors that send signals to the microprocessor in the leg, this way the hydraulic cylinders give the right resistance. Because the leg automatically adjust its settings, the risk of falling is significantly reduced. It's said you don't have to think about your steps anymore. Because of the artificial intelligence in the leg, a more natural and symmetrical gait is gained. This will ultimately save energy. The leg mechanism is proved to work well by walking down from stairs or uneven surfaces like a garden. Also cycling is possible, by adjusting your leg in a special mode (2nd mode). [9]

Ossür POWER KNEE:

Figure 3: POWER KNEE

The POWER KNEE, it's still the only powered prosthesis in the world with artificial intelligence. This is a prosthesis that is designed for above-knee amputees. The knee prosthesis works with a set of sensors located on the sound leg. In the knee is a computer which receives information from the sound leg. This way the POWER KNEE can mimic the lost proprioception, the unconscious ability of an organism to determine the position of the body [11], and muscle function. Especially proprioception is a great advantage. The information is send to the motor of the prosthesis which will make sure the amputee is able to perform a gait in a more natural way. The computer monitors the symmetry of the gait and adjusts it when needed. With this prosthesis the amputee is able to walk up the stairs step by step. Because the prosthesis actively lifts the heel off the ground, there is enough space between the toe and the ground. In this way stumbling can be avoided. So obstacles and ramps are easier to walk on. The knee prosthesis has a driven extension, which helps the amputee for example when rising from a chair. The POWER KNEE is also excellent for amputees who would like to walk a lot. The knee has a top walking speed of about 7 km/h. The prosthesis increases the overall locomotion speed of amputees. [12, 13, 14]

Ossür PROPRIO FOOT:

Normally, when you have two intact legs, you have two legs of the same length. When wearing a prosthesis, the prosthesis needs to be a bit smaller than your intact leg. This is needed for the swing phase. With two intact legs the ankle can perform dorsal flexion, so the leg is shorter and can swing past your other leg. Legs with two different lengths can cause wear on the back, hips and knees.

The first intelligent foot for transtibial amputees was brought out into the market in 2006 by Ossür. With this product, named PROPIO FOOT, it is possible to perform ankle flexion, including dorsal flexion. The PROPIO FOOT responds to different surfaces by automatically adapting the ankle in the right positions. The foot detects when the toe leaves the ground and response by dorsal flexion during the swing phase. This way the toe doesn't touch the floor, or surfaces that protrude. The foot makes it easier to climb stairs, by the adjusting possibility of the angle of the ankle. This prosthesis also helps amputees to sit and stand up easily. These techniques makes it possible for amputees to walk more naturally and with more confident, without the need to look constantly to the ground. The foot provides a more balanced, symmetric and confident gait. Another benefit is that the prosthesis had a shock absorption. The amputee will have more comfort in this way. As said before, a great problem with prostheses were the arisen wear on back, hips and knees. With this prosthesis foot, the chances of this are highly reduced. [12, 15]

Figure 4: PROPIO FOOT

Ossür RHEO KNEE:

The RHEO KNEE is also an artificial intelligent prosthesis from Ossür. It recognizes really subtle changes in walking speed and terrain. The knee learns from every movement the amputee makes, by adjusting the knee in different walking speeds. All the information about the gait of the amputee is stored in a kind of library. In this way, walking on the prosthesis is continuously improved.

The microprocessor in the knee determines the right knee resistance during the gait. The intelligent knee can recognize the different gait patterns, with the sensors which constantly monitors the weight of the user and the angle between knee and thigh.

The RHEO KNEE is for patients whose leg was amputated from the knee or with long transfemoral residual limb. The knee is lightweigthed prosthesis with a simple cosmetic finishing. It has a smooth swing movement that causes a natural and energy-efficient gait. [12, 14]

Figure 5: RHEO KNEE

Experiences with Intelligent Prostheses

Mobility is a really important aspect of our daily life. If there is a disruption in this mobility, it could change your quality of life dramatically. Because it is such an important aspect, a lot of studies in gait and movement sciences are made. Probably with the goal to improve our mobility, and with that our quality of life.

To be able to give a right answer to the main question, we have to look at the literature of the different studies. With the rise of the intelligent prostheses, there came more and more comparative research. There was said the intelligent prostheses were better than the conventional prostheses. So comparisons between the 'intelligent prostheses' and the 'conventional prostheses' were made. Some of these aspects are the energy use during walking or the amount of oxygen consumption.

Less energy, less effort

Oxygen consumption has been investigated in many studies. In one study the energy cost of walking, with comparison between intelligent prosthesis and conventional mechanism, is studied. The subjects had to walk on a treadmill at different speeds. Breath-by-breath analysis of the subject's expired air, determined average Vo_2 (L/min) within each period. When walking on a IP in another velocity than normal gait, less oxygen consumption has been found. Up to 5 to 9% reduction, despite the intelligent prosthesis is heavier than the conventional mechanism. However, in normal gait velocity there is no significant difference found. [20, 21]

The IP makes it possible for amputees to walk again, to walk again like before for almost 100%. Research showed that when young fit amputees undergo an appropriate rehabilitation program, they can achieve a incredible improved walking performance. Young amputees who used an IP were compared to able-bodied persons. The amputees had all undergone a prosthetic rehabilitation program of 8 weeks. This study showed that the most metabolically efficient walking speed for the IP users, was the same as for the controls. It also showed that young IP users could walk at normal speeds of able-bodied people with only 24% increase in energy cost. [22]

The intelligent prosthesis is said to be easy in use, because there is a reducing need for the subject to compensate for inappropriate movement. And with this the cognitive demand on the subject should be lessened. This claim was tested by BW Heller et al. in a pilot study comparing the intelligent prosthesis and conventionally damped knees. The subjects had to walk on a treadmill, which had constantly varying speeds. During walking, they had to execute a simple or complex distracting task. First they were asked to walk on conventional prosthesis, secondly they had to walk on the microprocessor-controlled leg.

Markers were used to see the ratio of sway during walking. The sway for complex task over the simple task was used as a measure of the degree of automation of gait. The conventional prosthesis had more sway. However, the outcome resulted in no significant differences between the two prostheses.

The conclusions of the study is that the microprocessor-controlled prosthesis was not found to be less cognitively demanding than a conventional prosthesis. This means the claim of the intelligent prosthesis to be less cognitive demanding, is not proven. [19]

Kaufman KR et al. studied the energy expenditure and activity of Transfemoral Amputees in a comparison situation. Using mechanical and micro-processor controlled knees. These tests were performed: Energy efficiency, Daily energy expenditure and the amputees were asked to fill in the Prosthesis Evaluation Questionnaire.

To obtain the energy efficiency, an accurate measure of oxygen cost under steady-state conditions was executed. Subjects breathed into a mouthpiece while walking on a controlled treadmill. The energy efficiency is the amount of oxygen needed to walk a unit distance. This was measured by a respiratory mass spectrometer. The energy efficiency was 2.3% lower with the microprocessor-controlled knee. However, the subject's perception was that it was easier walking with the intelligent leg.

Second, the daily energy expenditure (TDEE) was estimated. The DLW (Doubly labeled water) method was used. Hereby water containing 2 isotopes, Oxygen-18 and deuterium, were consumed. Urine samples were collected and examined. The difference in clearance of the two isotopes represented carbon dioxide production, which reflects energy expenditure. The TDEE was higher for microprocessor-controlled in comparison with the mechanical knee (14.1 vs 13.0 MJ/d). There was a significant 6% increase in TDEE due to physical activity. The subjects when using the mechanical knee paid 33% of their TDEE in physical activity. When they used the intelligent knee, they paid 39% to physical activity. The intelligent knee seems to support more physical activity in comparison with the mechanical knee.

The subjects also were asked to fill in a prosthesis evaluation Questionnaire (PEQ), to study the subject's perception of the 2 prosthesis. The PEQ is an questionnaire especially for persons with lower-limb amputations. The subjects gave in overall the microprocessor-controlled knee higher rates than the mechanical knee.

The final conclusion drawn from this article was that people ambulating with a microprocessor-controlled knee significantly increased their physical activity during daily life. And also experienced an improvement in their quality of life. [20]

Better movement, gait

Literature has been contradictory regarding gait characteristics. Some studies say there is an improvement in gait symmetry with intelligent prostheses. [21, 22] Other studies however show minimal gait changes. Namely Klute, et al. compared a microprocessor controlled knee (C-leg) with a non microprocessor controlled knee (Mauch SNS). They studied the functional mobility of lower-extremity amputees. The study demonstrated during constant speed ambulation, minimal differences between the gait biomechanics of subjects walking with the C-leg, compared with the Mauch SNS. [23]

In a study of gait and balance of transfemoral amputees, were passive mechanical and microprocessor-controlled prosthetic knees (C-leg) compared. With gait analyses, floor reaction forces were recorded and also motion measurements were made with markers. Balance as well was tested, with a computerized platform.

Patients using the mechanical prosthesis, had a ground reaction force in front of the knee during their gait. This causes the knee in a locked position, hyperextension, to obtain a mechanically stable

environment. The patients with the microprocessor-controlled knee had a normal walk with knee flexion during the loading response (stance phase).The balance test showed a poorer balance with the mechanical knee, than when using the C-leg.

According to this study, it appears that transfemoral amputees using a microprocessor-controlled knee (IP) have significant improvements in gait and balance. [24]

Another comparison between mechanical and microprocessor prosthetic knee control technologies is performed by Hafner BJ et al. Differences in function, performance and preference were evaluated.

Function measures were constant during the study. No significant differences were found.

With the evaluation of performance, the patients had to perform stair, hill decline and different surface exercises. In level ground test it appeared that the prosthetic side had an increased step length, however in the unaffected leg the step length did not change. This caused an increase in asymmetrical walk. When the subjects descended stairs, a trend of improved ability was found with the microprocessor knee. When ascending, there was no significantly difference found. Subject's hill descent with the intelligent knee had an increased step length on both the prosthetic-side and the sound-side. This caused a decreased time that was needed to descent the hill.

More comfortable, preference

In the study performed by Hafner BJ et al. preference of the patients between mechanical and microprocessor controlled knee was also evaluated. The patients were asked: " Which prosthesis do you prefer?". 14 of the 17 respondents preferred the C-leg. After four weeks, the patients had to rate how pleased they are with their current prosthesis. This showed even an increase of satisfaction in the C-leg. The patients had the choice to wear one of the prostheses between the tests. Later it showed that 94.4% of all steps were taken on the C-leg. [25]

Other aspects

As shown, there are many positive sides to the intelligent prosthesis found in literature. Most of the aspects that were found, were found in comparison studies. However, if you look in literature to negative aspects of the intelligent prosthesis, almost nothing is found.

A negative aspect can be the costs. It is presumably that the intelligent prosthesis will cost much more than the conventional prostheses. The IP contains more mechanics, a pneumatic/hydraulic system and a controller, etc. The higher the amount of components, the higher the risk of malfunctions. The IP therefore probably needs more maintenance, which also brings higher costs with it.

In one article, it was announced the intelligent prosthesis wasn't really compatible for elderly. But the reason why, wasn't explained. [26] However, an intelligent leg prosthesis you can compare with power steering. If you want to turn left, the power steering helps you to maneuver easily to the left. However if you only want to move a bit to the left but continue to drive straight, you don't want your steering wheel to move totally to the left. Than accidents will occur. Power steering is only there to help you, not to take over. With elderly this problem sometimes occur. They have problems with the automatic, the intelligent part, of the prosthesis. When walking, they tumble because they probably don't aspect the leg to adjust itself to the users gait pattern. [27]

Conclusions

During the years a lot of new developments have been made. There has been a lot of research about the intelligent prostheses. They are extensively compared with conventional prostheses. From the studies, numerous benefits have been demonstrated. When walking on a intelligent prostheses, it seems to take less oxygen consumption and causes a more natural gait pattern and balance improvements than with conventional prostheses. It also seems to increase the amputees physical activity during daily life. It lowers the increased energy expenditure more after amputation, in comparison to conventional prostheses. Climbing stairs and hillsides or walking over a irregular surface is also improved significantly during walking on an IP.

But the studies did not only test the effect of the leg during walking, the amputees were also asked to their preferences between mechanical and micro-processor controlled knee. The result was, that they preferred the intelligent leg. They also had the feeling that the intelligent leg was easier to walk on.

The designers of the intelligent leg also declared that the leg would be less cognitively demanding than a conventional prosthesis. However, in the study of Heller BW et al., the claim could not be proven.

While there may certainly be negative aspects to the intelligent prostheses, like higher costs and higher risk on malfunctions, none have been found in literature as said before. Known is, that intelligent prosthesis could work less with elderly, but no literature evidence is found.

This thesis was written to find an answer on the following question: Are Intelligent prostheses better than conventional prostheses? The comparison studies repeatedly showed that the Intelligent prostheses were better or the same as the conventional prostheses. And with the long list of advantages of the intelligent prosthesis in comparison to convention prosthesis, I can say that in my opinion the answer is yes. Yes, intelligent prosthesis are better than conventional prosthesis.

The developing and designing of intelligent prostheses is far from over. The future is likely to provide many improvements. Fifty years earlier, people would never have thought something like the intelligent leg prosthesis was even possible. So who knows what the future will bring to the prosthetic field.

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