Perception of walking surface by transtibial amputees

- A pilot study

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Sammanfattning

Titel: Transtibialt amputerades varseblivning av gångunderlag – En pilotstudie

Syftet med studien var att;

- undersöka om det är möjligt för en amputerad att identifiera gångunderlag genom informationen de får via protesen.
- undersöka om det existerar några mätbara förändringar i den amputerades gångmönster på olika underlag.

Metod


Resultat

Överensstämmelse mellan det verkliga underlaget och det som rapporterades av försökspersonen var godkänt till bra ($k=0.58$). En two way repeated measures ANOVA visade en signifikant skillnad gällande lateral knärörelse mellan hälisättning och framfotsisättning, med huvudeffekt för gångunderlag ($p=0.010$).

Slutsats

Amputerade har en godkänt till bra förmåga att identifiera gångunderlag utan extra information från syn, hörsel eller från det friska benet.

Kinematiska data visade en signifikant ökning av lateral knärörelse mellan hälisättning och framfotsisättning på det vinklade underlaget jämfört med både det plana och det mjuka underlaget. Detta gällde för både amputerad och frisk sida.

Tiden för hälisättning till framfotsisättning var ej påverkad av gångunderlag, och inte heller av om det var första eller andra steget.

Nyckelord: gångunderlag, perception, proprioception, protes
Summary

The aims of this study were to;

- determine if it is possible for amputees to identify walking surfaces by receiving feedback through their prostheses.
- determine if there are any measurable changes in amputee gait characteristics when walking on different surfaces.

Methods
Subjects walked on a specially built walkway with exchangeable surface materials (level, soft and tilted) with visual and audio feedback occluded. Subjects were required to identify the surface material. Kinematic data were collected simultaneously.

Results
Agreement between the true surface and that identified by the subject on the amputated side was fair to good ($k=0.58$). A two way repeated measures ANOVA showed a significant difference in lateral knee displacement between heel contact to foot flat, with main effect for surface ($p=0.010$).

Conclusion
Amputees have a fair to good ability to identify walking surfaces without additional information from eye sight, hearing or the sound limb.

The kinematic measures showed a significant increase in lateral knee displacement between heel contact to foot flat on the tilted surface compared to both level and soft surfaces. This was the case for both the amputated and the sound side.

The duration of heel contact to foot flat was unaffected by walking surface and first or second step.

Keywords: perception, proprioception, prostheses, walking surface
Introduction

Perception is something we usually take for granted when it comes to understanding and identifying what surfaces we walk upon. For amputees however, perception has been compromised. Other groups of patients can suffer losses from peripheral sensory input, e.g. peripheral neuropathy in diabetes mellitus. In those patients, it has been reported that there is an increase risk of falling and a change in perceived safety, as well as a decrease in quality of life (van Schie, 2008).

Assuming that prosthetic users can be compared to other groups with compromised sensomotoric input, it is worth noting that modern prostheses offer a variety of dynamic functions to make sure the foot is in full contact with the ground and that no harmful forces are transferred to the stump. There are prosthetic liners, shock-absorbing pylons and prosthetic feet, all which mainly have two focus areas: comfort and energy efficiency. What we do not know is how these functions affect sensory information to the amputee through their prosthesis and residual limb from the walking surface.

There is one study on how different socket designs affect the somatosensory input in transtibial amputees (Rusaw, 2006). Rusaw concluded that the prosthetic liner did not affect proprioception. However, these results were obtained during seated tasks so it is not known if sensory information from the walking surface actually reaches the socket level during gait. How different prosthetic feet affects sensory information is not known.

Another aspect of the ability to identify surface lays in the choice of prosthetic feet components. The results from the present study will hopefully give insight in how to test different prosthetic feet with regards to sensory abilities. This could give both manufacturers and prosthetists a better insight in how their constructions affect the patient’s information of the world around them, and could potentially also affect risk of falls.
**Aims:**

- determine if it is possible for amputees to identify walking surfaces by receiving feedback through their prostheses.
- determine if there are any measurable changes in amputee gait characteristics when walking on different surfaces.
Background

Proprioception & balance

Unlike our five exteroceptive senses by which we perceive the outside world, and interoceptive senses, by which we perceive pain and stretching of internal organs, proprioception is a third part of our sensory system that internally provides feedback on the status of the body. It is the sense tells us where the various parts of the body are located in relation to each other and to the ground (Sherrington, 1907). Proprioception is often defined as sensation, or perception, of movements and forces affecting the body. Proprioception is something that is mostly happening on an subconscious level. The information for this perception of the world around us comes from a combination of nerve terminals in muscles and tendons, the fibrous capsules around joints and information from the vestibular system (Stedman, 2003). The peripheral nervous system relays proprioceptive information to the central nervous system (CNS). Within the CNS, an integration of data from limb position, motion, vestibular and visual information is performed, and a motor response is initiated to answer to the given information and to uphold postural balance.

Proprioception & balance in transtibial amputees

In this study a comparison was done between the amputee population and other populations suffering form decreased afferent information, such as e.g. diabetics suffering from neuropathy. The reason for this comparison is that transtibial amputees walking on a prosthetic foot have been shown to suffer from similar changes of gait characteristics as other groups with peripheral neurological deficiencies, e.g. diabetes mellitus (Powers et al., 1994).

Should one or more systems fail regarding proprioceptive information to the CNS, it will increase the demand on the remaining systems. (Courtemanche et al., 1996) presented in their study on diabetics how attentional demand during walking was increased when suffering from decreased sensory input. They also stated that
increased attentional demand might be a risk when faced with challenges during walking, such as obstacles in the way, and that this leads to increased risk of falls.

Since a transtibial amputee has an altered physiology, such as loss of soft tissue, bone and sensory receptors in the amputated limb, the way they perceive their surroundings will also differ from that of a non-amputee. They do no longer receive sensory information the way they used to from their leg, and the information they do get comes in different ways that the amputee will have to learn to understand. They have lost their foot, a body part with high amount of mechanoreceptors, that are of great importance for maintaining posture and balance (Ducic et al., 2004; Meyer et al., 2004). Instead they now have to rely on information transferred via a mechanical leg onto the residual limb, a surface not designed to handle this type of information.

The visual and vestibular systems are not affected by the amputation in itself. They may, however, be affected by conditions like diabetes mellitus that has a high prevalence amongst amputees (van Schie, 2008).

It has been shown that diabetics alter their postural control mechanism when it comes to detect perturbations (Kim and Robinson, 2005). If this holds true for the amputee population we can not know for certain. There is also a change over time regarding what senses the amputees rely upon to gain information about the walking surface. Early on in rehabilitation they are very dependant upon visual feedback, but as time goes by this visual dependency decreases and closes in on the normal, due to the fact that it takes central reorganization to adapt to the peripheral sensory and motor impairments (Geurts et al., 1991).

The amputee population has also been shown to have a impaired balance compared to non-amputees both regarding static and dynamic balance (Buckley et al., 2002), which makes them more likely to fall. The transtibial amputee is lacking an active control of the ankle/prosthetic foot, which also affects the motor response initiated by the CNS. The loss of the anatomical ankle also leads to negatively affected ankle strategy to maintain balance (Aruin et al., 1997). This lack of ankle control is something that all amputees must adapt to and that must be kept in mind when conducting training.
**Risk of falling**

The above mentioned decrease in proprioception and balance puts the amputee at high risk for fall and injury. This is not just a problem for the amputee, but also of economic importance for the society. Falls in general were in 2006 estimated to cause direct and indirect costs in the US of $75-$100 billion per year (Urton, 1991). Even if these data are from the US it is clear that falls are a great risk that carries a big economic burden, as well as personal suffering.

Not only are falls a great risk in the general population, but the amputees has further increased risk of falling compared to the able-bodied population. In total 52.4% of the lower limb amputees in one study reported falling in the last year (Miller et al., 2001b), compared to the 30% of all 65+ community dwellers (Lord et al., 1994). Special challenges for the amputee includes absence of sensory feedback from the foot, changes in lower limb weight distribution and problems coordinating the movement of the new limb (Pauley et al., 2006).

To assess the risk of falling balance confidence was shown to be the strongest indicator judging if a patient is at risk or not (Miller et al., 2001a). In another study Miller *et al.* also showed that lower limb amputees has a reduced level of balance confidence compared to an able-bodied control group (Miller and Deathe, 2004). In the same study Miller and Deathe also stated that there is a strong correlation between balance confidence and fear of falling, indicating that simply asking a patient whether they have fear of falling is a quick indicator of their balance confidence. This, in turn, helps to do a quick risk assessment. Another factor that has been identified as an indicator for high risk of falls is the inability to make quick steps in different directions (Dite and Temple, 2002), which is something that is likely to be a challenge for a lower limb amputee. This ability of fast steppage is important when walking surfaces change to sudden inclinations, tilts or slippery surfaces.
**Visual dependencies**

It was of importance for this thesis to look into how subjects are affected by blocking their lower field of vision (LFV). Normally, people tend to fixate approximately two steps ahead when walking on irregular terrain (Marigold and Patla, 2008). The peripheral contribution from LFV give information about how the movement trajectory needs to be adjusted. What happens then, if you block the LFV? It has been shown that blocking the LFV results in decreased walking velocity, as well as shorter step length when walking across multi-surface terrain (Marigold and Patla, 2008), facts that were considered when building the walkway for the current project. Since amputees in many cases suffer from diabetes that, in turn, leads to decreased eyesight, it also of general interest for the prosthetists to know how visual ability might affect gait patterns, and in extension the general activity level of the amputee.

**Prosthetic feet characteristics**

The number of prosthetic feet available on the market has exploded in recent years, and probably the most common argument for the new products is that they are energy storing. This, together with the fact that new amputees keep track of the market via Internet to a larger extent than before and thus see all new products, has put pressure on the clinicians to choose a high tech product. But what is the evidence for the new feet being better than the old conventional ones? Several studies, with various quality of evidence, have been done in the area and there is also a systematic review available (Hofstad et al., 2004). However, the focus of most studies are all about two areas; comfort and energy consumption. Comparison between different feet designs has been done in several ways; using questionnaires(Casillas JM, 1995; Postema et al., 1997), kinematics(Casillas JM, 1995; Torburn et al., 1990), kinetics(Schmalz et al., 2002) and energy consumption(Schmalz et al., 2002; Hsu et al., 1999). To the author’s knowledge there are no studies done regarding the sensory input to the patient via the prosthetic foot.
Research Design

Subjects

Three subjects volunteered to participate in the study. They were all unilateral transtibial amputees and fulfilled the inclusion criteria listed below. Their individual details are shown in Table 1.

Inclusion criteria

Subjects had to fulfill the following criteria:
1. transtibial amputee,
2. in good health, i.e. no vascular or neurological problems,
3. have no vestibular disorders,
4. have good eye sight, with or without corrective lenses
5. have a current prosthesis with good fit and function,
6. have used the prosthesis regularly for at least one year,
7. have no problems regarding the status of the stump or the contralateral limb.
8. be able to fill in a written form of consent for participation in the study,
10. be above 18 years old.

Table 1. Subjects’ characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age</th>
<th>Prosthetic foot</th>
<th>Prosthetic liner</th>
<th>Prosthetic suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>71</td>
<td>C-walk (Otto Bock)</td>
<td>3mm Dermo Liner (Össur)</td>
<td>Pin suspension</td>
</tr>
<tr>
<td>2</td>
<td>Male</td>
<td>37</td>
<td>Pathfinder (OWW)</td>
<td>6mm Alpha Liner (OWW)</td>
<td>Sleeve</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>58</td>
<td>Renegade (Freedom Innovations)</td>
<td>6mm Cool Liner (Össur)</td>
<td>Harmony vacuum system (Otto Bock)</td>
</tr>
</tbody>
</table>


**Equipment**

The subjects’ ability to identify the walking surface was tested on both the prosthetic limb and the sound side. The subjects did not see the walking surface, since their lower field of vision was blocked but they had their eyes open to not unnecessarily impair their balance by totally excluding visual input.

The subjects were required to walk on a specially built walkway out of plywood where the surface and inclination in the frontal plane varied, and could be changed individually for each leg (picture 1).

The walkway was 4500x520x55mm (LxWxH), with the exchangeable surface material being 1500mm long. This gave a start and stop length of 1500mm, just enough to start with the contralateral foot and place the first step of the foot to measure on the test surface.

Three different surfaces were selected; Level (same as the rest of the walkway), Soft (40mm thick, 20 shore closed cell foam plastic) and tilted (declined 5 degrees laterally). These are all surfaces that have been used in a previous study on non-amputees (Marigold and Patla, 2008). The difference from that study is that the inclination was changed from 10 degrees to 5 degrees. This was done out of practical reasons as the constructed walkway could not incorporate a 10 degree slope. After testing it on an amputee test patient 5 degrees was found to be a suitable level of inclination resulting in an increase in lateral knee displacement without being to obvious.

Three trials were performed on each surface, giving a total of nine trials per leg. The subject typically walked two steps on the prepared surface. The reason for not making the test surface longer and measuring more steps was that the primary interest of this study was to look on how subjects reacted immediately after stepping onto the unknown surface and if/ or how they made any corrections. A second step was also included to see if the subjects adapted the gait to the surface between the first and second step.
Identification data

At the end of each trial the subjects identified what type of walking surface they had been walking on and the answer was noted. The only information given about the surfaces was that they would need to identify **level**, **soft** or **tilted**. There was no information given about the direction of the inclination of the tilted surface.

To occlude audio clues about the surface, there was a distinct difference in sound walking on the soft surface compared to the other surfaces, the subjects had an mp3 player playing loud music. To prevent visual clues they had a Lower Field of Vision Prohibitor Unit (LFVPU), specially designed for this project (picture 2). This was designed and adjusted so that the subject could see approximately 5-10 degrees down from a horizontal plane, meaning they could not see any part of the walkway. They could however see the rest of the room.

If the subject for some reason hit the edge of the test surface, the trial was still saved and used, since repeating it would give unfair advantage in identifying the surface. If such a trial was made it was noted and taken into consideration when doing the instrumented gait analysis since it could potentially affect the kinematic parameters used.

Kinematic data

Simultaneously with the surface identification test, kinematic measurements were performed using a 6 camera three dimensional system at 100Hz (Qualisys Medical AB, Gothenburg, Sweden).

The marker setup used included three foot markers and one knee marker. Foot markers were placed on MTH I and MTH V and on the same height from the ground on the posterior aspect of the
heel, and corresponding on the prosthetic foot (picture 3). The knee marker was placed on the lateral side of the knee at the position of the knee joint centre.

**Randomization**

The order of which all surface trials were performed, as well as the order of amputated and sound side, was randomized using the rand() command in Excel.

**Video**

Video and photo were used to record the setup and trials for additional possibility to control events.

**Safety**

Each subject’s safety was guaranteed by using a safety rail along the walkway, as well as having an assistant guiding them when needed.

**Data analysis**

Kinematic data were analysed in Visual3D software (C-motion, Inc., Rockville, MD, USA) to see if there were any measurable differences in how they adapt the gait to the walking surface between the first and second step, as well as to see if there was any objective changes in knee kinematics as a result of the different walking surfaces. Duration of heel contact to foot flat expressed as percentage of the stance phase, and lateral displacement of the knee in the frontal plane during stance phase expressed in mm of mediolateral movement were calculated, divided into heel contact to foot flat and foot flat to toe off. Lateral knee displacement was measured using the function Generate Metric Min/Max in Visual 3D, calculated on the y-axis (mediolateral movement), for each set time frame. Total displacement was thus calculated as:

\[(Lat. \text{ Displacement})=(Metric \text{ Max})-(Metric \text{ Min}).\]
**Statistics**

The identification test was analysed using Cohen’s Unweighted Kappa, to take into account the chance of guessing. The result was interpreted according to the following categorization by Fleiss (1981):

- $<0.4$: Poor agreement
- $0.4-0.75$: Fair-to-good agreement
- $>0.75$: Excellent agreement

The gait characteristics were analysed using a two way repeated measures ANOVA, using $p<0.05$ as significance level. Tukey’s post hoc analysis was used to identify differences.

**Ethical approval**

Ethical approval has been given by the regional board in Linköping, Sweden. All subjects read and signed an informed consent form.
Results

*Identification test*

*Amputated side*

Results are presented in Table 2, A-C.

Subject 2 did something we had not anticipated during this test; he added a fourth category to his identifications, tilted inwards. This is why in the table he has four categories in his answers, even though there were only three surfaces tested.

*Table 2, A-C. Surfaces as identified by subjects per trial.*

**A. Level surface**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>Level</td>
<td>Level</td>
<td>Level</td>
</tr>
<tr>
<td>Trial 2</td>
<td>Level</td>
<td>Tilted</td>
<td>Level</td>
</tr>
<tr>
<td>Trial 3</td>
<td>Level</td>
<td>Level</td>
<td>Level</td>
</tr>
<tr>
<td># correctly identified</td>
<td>3/3</td>
<td>2/3</td>
<td>3/3</td>
</tr>
</tbody>
</table>

**B. Soft surface**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>Level</td>
<td>Soft</td>
<td>Soft</td>
</tr>
<tr>
<td>Trial 2</td>
<td>Level</td>
<td>Tilted in</td>
<td>Soft</td>
</tr>
<tr>
<td>Trial 3</td>
<td>Soft</td>
<td>Level</td>
<td>Soft</td>
</tr>
<tr>
<td># correctly identified</td>
<td>1/3</td>
<td>1/3</td>
<td>3/3</td>
</tr>
</tbody>
</table>

**C. Tilted surface**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>Soft</td>
<td>Tilted</td>
<td>Tilted</td>
</tr>
<tr>
<td>Trial 2</td>
<td>Tilted</td>
<td>Tilted in</td>
<td>Tilted</td>
</tr>
<tr>
<td>Trial 3</td>
<td>Tilted</td>
<td>Tilted in</td>
<td>Tilted</td>
</tr>
<tr>
<td># correctly identified</td>
<td>2/3</td>
<td>1/3</td>
<td>3/3</td>
</tr>
</tbody>
</table>
As seen there was a difference between the subjects’ ability to identify surfaces, ranging from subject 3 with all correct to subject 2 with 4/9 correct answers. The soft surface seems to be the hardest to differ from the other surfaces, while the level surface being the easiest.

**Sound side**

All the subjects identified 100% of the surfaces correctly on the sound limb.

**Statistics**

Due to this thesis’ small number of test subjects and trials no statistics were used on the individual subject. As a group, Cohen’s Unweighted Kappa on the identification test for the amputated side reported Observed Kappa as 0.58, indicating a fair-to-good ability to identify surfaces with the prosthetic limb.

The tests on the sound side ended with all subjects answering 100% correct, and thus reached a Kappa value of 1 indicating excellent agreement.

**Spontaneous comments**

Following are comments stated by the subjects while doing the test:

**Subject 1**

“…if I don’t know I am guessing for level surface”.

**Subject 2**

“This was much harder than I thought, really tough to know.”

**Subject 3**

“If I feel an increased pressure on the inside of the knee, I know it is a surface tilting outwards. When it feels like my foot takes longer time to leave the ground, kind of hangs on to it, I know it is a soft surface.”
Kinematics

Duration of heel contact to foot flat as percentage of stance phase

*Amputated side*

As a group this test showed no consistent pattern of change between step 1 and step 2 regarding duration of heel contact to loading response. Furthermore no significant differences between surface materials were found (figure 1).

*Figure 1. Duration of heel contact to foot flat as part of stance phase for the amputated side.*
**Sound side**

As on the amputated side there were no significant differences in between steps, or surfaces. There was a decreased duration of heel contact to foot flat as percentage of stance phase compared to the amputated side (figure 2).

![Bar charts for Subject 1, 2, and 3 showing percentage distribution of steps and levels](image)

**Figure 2. Duration of heel contact to foot flat as part of stance phase for the sound side.**

**Statistics**

A Shapiro-Wilk test for normality was performed and achieved results >0.05 on all categories, indicating that parametric tests could be used.
A two way ANOVA with repeated measures for step and surface showed no significant differences.

**Lateral knee displacement in heel contact to foot flat**

*Amputated side*

The tilted surface caused higher lateral displacement of the knee than the other surfaces, the tendency being that step 1 had a greater difference than step 2 (fig.3).

*Figure 3. Lateral knee displacement for the amputated side during heel contact to foot flat in mm for step 1 and step 2 on the different surface materials.*
**Sound side**

Here the same tendency as in the amputated side is seen, the tilted surface showing greater displacement and more so in step 1 than in step 2 (fig.4). Note also that the values are generally lower for the sound side compared to the amputated.

![Bar charts for subjects 1, 2, and 3 showing lateral knee displacement for the sound side during heel contact to foot flat in mm for step 1 and step 2 on the different surface materials.](image)

**Figure 4.** Lateral knee displacement for the sound side during heel contact to foot flat in mm for step 1 and step 2 on the different surface materials.

**Statistics**

A Shapiro-Wilk test for normality was performed and achieved results >0.05 on all categories, indicating that parametric tests could be used.
A two way repeated measures ANOVA was performed and showed a significant difference in lateral knee displacement, with main effect for surface (p=0.010). Tukey’s post hoc analysis revealed that the tilted surface was significantly different in lateral knee displacement compared to both the level surface (p<0.05), and the soft surface (p<0.05). There was no difference between the level and soft surfaces (p>0.05). There was no interaction effect between surface and step (p>0.05). There was no difference found between amputated side and sound side (p>0.05).
Lateral knee displacement in foot flat to toe off

Amputated side

In this part of the gait cycle there was no clear differences regarding lateral knee displacement (fig.5).

Figure 5. Lateral knee displacement for the amputated side in foot flat to toe off in mm for step 1 and step 2 on the different surface materials.
**Sound side**

As on the amputated side there is no clear tendencies regarding lateral knee displacement. In this part of the gait cycle there is not the same tendency of lower values for the sound side compared to the amputated (fig.6).

*Figure 6. Lateral knee displacement for the sound side in foot flat to toe off in mm for step 1 and step 2 on the different surface materials.*

**Statistics**

A Shapiro-Wilk test for normality was performed and achieved results >0.05 on all categories, indicating that parametric tests could be used.
A two way repeated measures ANOVA was performed and showed no significant difference in lateral knee displacement, with main effect for surface (p>0.05). There was no difference found between amputated side and sound side (p>0.05).
Discussion

Identification test
The result showed a fair to good ability to identify different surfaces via the prosthetic limb (Observed Kappa 0.58) (Fleiss, 1981). It is a result that was raised considerably by subject 3 that had 100% correct identifications. With this small sample size it is hard to draw any decisive conclusions on whether subject 3 is exceptional, or if the result reflects the true situation for the amputees.

Subject 1
The comment made by this subject, regarding guessing for level surface if unsure, could partly explain why he had 5/9 identifications as being level surface. He had all three trials on the level surface correct but how many of those that were uncertain trials that he stated as level we cannot know from this test.

Subject 2
An interesting response from this subject was the addition of a fourth category of surfaces, namely “tilted in”. In the instructions given there was no information given on the direction of the tilted surface which might have been a mistake in the setup of the test. At the same time, this inability to know if a surface tilts in or out, would probably not have been visualized if we had given instructions regarding the direction of the tilt. The subject identified 2/3 trials on the tilted surface as being tilted in the opposite directions, indicating that this subject is insensitive to changes in the frontal plane.

Subject 3
This subject had 100% correct identifications on both legs. The subject had a very precise explanation regarding how to identify surfaces. The subject’s statement, about how to interpret forces, would indicate that specific training could improve amputees’
ability to identify surfaces, something that would be worth investigating further. Considering that subject 3 spends a lot of both his work and leisure time in the forest he is by far the subject most exposed to varying surfaces, which might have given him his good ability to identify surfaces. Subject 3 had a vacuum socket design, meaning a tighter fit to the residual limb, which could have given him an extra advantage in perceiving the movement happening at the knee when walking on the tilted surface. However, Rusaw (2006) found that the choice of liner and suspension did not affect proprioception of movement in the sagittal plane, which indicates that it might not be an issue in this study either.

**Duration of heel contact to foot flat as percentage of stance phase**

This test that was performed to see if the subjects did adapt on the second step for a new surface showed no statistically significant changes at all, neither on the sound or the amputated side. This result could be affected by the fact that all subjects walked slower and with a shorter step length than they would normally do, which is a known effect of limiting the lower field of vision as stated in the background. The gait pattern used might then be what would usually reflect their choice of gait on unknown/dangerous surfaces, slower gait and shorter step length. If that was the case, it is not surprising that no changes were seen between first and second step, since they were already walking slowly all through the test. The small differences found could be reason to consider using more trials in future work, as to see if there is any real difference or not. The subjects do spend more time in heel contact to foot flat as part of stance phase on the amputated side compared to the sound side. This could potentially negatively affect their ability to identify surfaces, since they spend more time in an unstable condition without the whole foot on the ground.
**Lateral knee displacement**

Regarding this test, the only significant difference found was that the knee had a larger lateral displacement on the tilted surface, compared to both others surfaces, during heel contact to foot flat response. This indicates that the subjects do have an objective change at the knee level on tilted surfaces, meaning that none of the prosthetic feet in this study prevented that information from reaching the knee where it can potentially be used to identify the change in surface angle. However, only one subject within this study knew how to use this information to identify the surface. It also indicates that not controlling for prosthetic feet components did not affect the test in terms of movement in the frontal plane.

In the part of the gait cycle from foot flat to toe off, there were no significant changes between any of the surfaces regarding lateral knee displacement. Thus the change in lateral knee movement happens during heel contact to foot flat. During the rest of stance it does not change more than compared to a the other surfaces.

It is worth noting that the sound side had less displacement on average than the amputated during heel contact to foot flat, indicating, as expected, that the prosthetic feet do not have the ability to adjust as quickly to the surface in the frontal plane as an anatomical foot.

Two thirds of the subjects could not translate this significant change in lateral knee displacement during heel contact to foot flat into useful information about the surface. This supports the idea that it might be possible with training directed towards surface recognition for amputees. It does seem like amputees need help to recognise these new stimuli, and a follow up study with pre/post targeted training on surface recognition would be of great interest. As mentioned earlier subject 3 had a very exact, and rather simple, definition of his strategies for identification. He knew how to translate an increased force to the medial side of his knee as a surface tilting out, and vice versa for lateral pressure. He had also learned to identify the prolonged push off resulting from a softer, more compliant material, and could thus get a feeling for how hard/soft a surface is just using the information form the prostheses. These comments could help making guidelines for specific training regarding walking surfaces.
Limitations

The present study has quite a few limitations worth consideration.

First, there was a small sample size, meaning that the statistical value of the result is limited. For continued studies, following the model of this thesis, there would be a need for more subjects and possibly more repeated trials.

The reliability of the data has not been confirmed. It would have been beneficial to test the between-day reliability of at least one subject to make sure the result was repeatable and to what extent guessing might be a factor.

Unfortunately, measuring several different prosthetic feet on each subject which was intended, could not be performed. Should this have been done, it would hopefully have given a better understanding about how the choice of prosthetic feet affects the ability of surface recognition.

Directions for future research

Future studies using the presented method should focus on comparing different components and control for same components used in all subjects. This would give the professional field of P&O more usable data, which could then potentially affect prescription of prosthetic components with patient safety in mind, not just comfort and energy consumption.

Since there was no sign of adapting gait pattern between step 1 and step 2 the results within this thesis indicates that data collected from step 1 would be sufficient, this would also make it easier to make sure that one step is a clean hit compared to having to incorporate two steps on each trial. The result of this study could also be used to support only doing the identification test since the lateral knee displacement was significant in all prosthetic feet used as well as in the sound limbs. This would make the method easier to use in a clinical setting for evaluation as well as training.
Conclusions

The present study indicates that transtibial amputees have a fair to good ability to identify level, soft and tilted walking surfaces, without additional information from eye sight, hearing or the sound limb.

The objective measures in this study showed significant increase in lateral knee displacement between heel contact to foot flat on tilted surfaces compared to both level and soft surfaces. This was the case for both the amputated and sound side. This difference existed in both the first and second step, with no difference between steps.

The duration of heel contact to foot flat as part of stance phase was unaffected by walking surface and if it was first or second step on the surface.
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