*Prosthetics and Orthotics International*, 1999, 23, 13–20

# Relaxed versus activated stump muscles during casting for trans-tibial prostheses

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**Abstract**

In prosthetic practice, the question often arises as to whether the hand cast should be made from a contracted or from a non-contracted amputation stump. To elucidate this question, the authors have performed a study to quantify the volume difference between these 2 conditions, and to relate the differences to prosthetic fitting. Sixteen (16) trans-tibial amputees participated in the study. All of them were fitted with an ICEROSS silicone socket. Electromyographic studies, with electrodes attached to the anterior tibial and medial gastrocnemius muscles, were carried out to determine muscle contraction levels. Volume determinations were made with the CAPOD laser scanning system. Measurements were performed with and without the silicone liner on the stump. Without a silicone liner, the volume of the stump increased by 5.8% (SD=5.3) as the muscles contracted. This increase was statistically significant. With the liner donned the volume increased 3.5% (SD=3.3). This increase was also statistically significant. The volume of the prosthetic socket was also compared with the stump volume with a silicone liner on. For the relaxed stump, the difference was 1.8% (SD=10.1), and for the contracted stump -1.7% (SD=11.3). Neither difference was statistically significant. The importance of these volume changes and how they influence stiffness of the coupling between the stump and the socket are discussed. It is concluded, that the observed difference in volume between a contracted and a non-contracted stump are large enough to be considered by the prosthetist in his decision on how to make a hand cast.

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## Introduction

A major deficiency in some modern educational programmes in prosthetics and orthotics is the lack of theoretical knowledge for the production of optimal prostheses and orthoses. During training in prosthetics, one of several questions that arises from the students is whether the patient should activate the stump muscles during the casting process for a trans-tibial prosthesis, or if the casting should be performed on a relaxed stump. Generally, the patient is asked to try to relax all stump muscles, and, depending on which type of socket is to be used, the patient is instructed to keep the knee extended or slightly flexed. However, no theoretical basis for this procedure has been found in the literature. Today, students (and many practising prosthetists) demand a theoretical basis for casting and other procedures.

It is well known that a muscle increases in cross-sectional area over the belly when the muscle is contracted. If the muscles in the trans-tibial amputation stump follow the same pattern, and the prosthetist does not consider this phenomenon, the socket fitting could be jeopardised. The truth behind a well-fitted socket is a total control over all the different parameters. Burgess *et al.* (1974) investigated the possibilities of using trans-tibial muscle activity to control socket suspension.

Radcliffe and Foort (1961) described the traditional way of manual casting for a patellar-tendon-bearing (PTB) prosthesis. They introduced a complete technical procedure for making a PTB prosthesis and their technique has more or less become standard. Today, it is a common opinion that prosthetic fitting should be based on total contact and total weight-bearing (Kapp and Cummings, 1992; Klasson, 1995). One way to achieve this is to use silicone liners together with a controlled hand casting technique (Kristinsson, 1993; Fillauer *et al.*, 1989). In order to improve total contact with an ICEROSS liner, the ICEX technique can be used, i.e. the socket is produced under hydraulic pressure applied to the stump. This new concept, however, puts new demands on the prosthetist and his/her knowledge and technique. Ever since computer aided design/computer aided manufacture (CAD/CAM) was introduced, it has been seen as a complement to the traditional hand casting technique. The different CAD/CAM systems on the market today can be divided into 2 distinct groups: one using a plaster cast negative as the starting point (e.g. ShapeMakers) and the other using a non-contact scanning technique, measuring directly on the amputation stump (e.g. CAPOD Systems) (Brüssel, 1991). Both techniques have, when correctly used, the potential of producing total contact and total weight-bearing prostheses. The use of a non-contact scanning technique eliminates the necessity to make a correct hand cast. This technique, however, puts new demands on the prosthetist's skill at designing a high quality socket.

The ultimate goal for the prosthetist, no matter what casting technique is used, is always the rehabilitation of the patient by means of a well-fitted prosthesis. This goal can be reached by giving special attention to the interaction between prosthetic socket and amputation stump during prosthetic fitting. The properties of the stump/socket interface depend on the initial hand casting and the subsequent rectification of the positive plaster mould. The aim is to establish a flexible coupling between the stump and the socket that is able to transfer ground reaction forces from the prosthesis to the skeleton (Klasson, 1995). If the stiffness of this flexible coupling is low, the skeleton and the soft tissues inside the socket will move during gait and the patient will experience less stability (Lilja and Johansson, 1993; Grevsten and Eriksson, 1975; Eriksson and Lemperg, 1970). If, however, the coupling is too stiff due to an overly confined fitting, severe problems can occur, for example decreased blood flow. Levy (1983) describes several stump problems related to blood circulation as well as problems related to increased pressure between the stump and the socket e.g. ischemic ulcers, stasis dermatitis.

Muscular activity patterns during gait are dependent on walking speed, fatigue etc. (Whittle, 1991). In the amputation stump, muscle activity during gait is similar to that found during normal gait for non-amputees. This activity can be described as a common activity pattern, but there is a difference between amputees and non-amputees with respect to order of muscle activation, activity level etc. (Whittle, 1991; Basmajian and De Luca, 1985). Grevsten and Stålberg (1975) have described this in electromyographic studies. Among amputees, muscle activity not only accounts for motion of the stump, but even contributes to the suspension of the prosthesis (Burgess *et al.*, 1974; Lilja and Öberg, 1998). With this in mind, the question of relaxed versus contracted stump muscles during casting is relevant and not trivial from the prosthetist's point of view.

The most rigid flexible coupling between the prosthetic socket and the amputation stump should appear when maximum forces are transferred from the prosthesis to the skeleton. If the movements of the skeleton inside the prosthetic socket are not minimised, and if there is a discrepancy between the shape of the amputation stump and the shape of the prosthesis, severe stump problems can occur, for example maceration, abrasion and blister formations (Levy, 1983; Lilja and Johansson, 1993). The volume of the amputation stump fluctuates over time after the amputation (Lilja and Öberg, 1997). The stump volume may also vary due to changes in blood perfusion during muscular activity. The volumes of the amputation stump and the socket are closely related to the fit of the prosthetic socket. Significant differences between the volume of the amputation stump and the volume of the prosthetic socket reduce the possibility of a good fit and thereby a successful rehabilitation. Conversely, a better-fitted prosthetic socket will reduce stump problems and improve the rehabilitation process. Patients' opinions, however, about a good fit do not always correspond with the prosthetist's, and this might be a problem during rehabilitation of the amputee. It is important to stress that the amputee and the prosthetist must share the same goal with respect to prosthetic fitting and rehabilitation.

Very few studies have been published on the influence of muscle contraction on the fit of the prosthesis, and the existing studies are few, and relatively old and incomplete in this respect.

## Aim

The aim of the present study was to:

- quantify the difference in volume between a non-contracted and contracted amputation stump;
  - discuss such volume differences in relation to prosthetic fitting.

The hypothesis was that the muscle activity influenced stump volume, and this must be considered during hand casting for trans-tibial prostheses.

## Material and methods

*Subjects*

Seven (7) men and 9 women, with a mean age of 72 (57-83), were included in the study. Thirteen (13) patients were amputated due to arteriosclerosis with or without diabetes mellitus and 3 patients were amputated due to trauma. Three (3) patients were amputated with a sagittal flap technique and the remaining patients with a long posterior flap. Before and after amputation all patients were able to walk with or without crutches. Four (4) of the patients had used a temporary prosthesis prior to being fitted with the definitive prosthesis. The patients were included in the study at least 6 months after amputation. All patients were definitively fitted with an ICEROSS silicone liner in their ordinary rehabilitation and 14 of 16 used their prosthesis every day, between 2 and 16 hours a day. One (1) of 16 patients used an ICEROSS silicone liner with a lanyard kit, the others used the ICEROSS with a bayonet coupling. Thirteen (13) amputees used an Otto Bock single axis foot, 2 used an Otto Bock Dynamic Foot and 1 used an Otto Bock Greissinger Foot.

*Questionnaire*

All amputees were interviewed according to the Prosthetic Profile of the Amputee questionnaire. Grisé *et al.* (1993), who also evaluated the questionnaire according to validity and reliability (Gauthier-Gagnon and Grisé, 1994), designed the questionnaire. To the original questionnaire, a second section, designed for the present study, was added and included questions pertaining to the design and function of the prosthesis, from a prosthetist's point of view. The number of patients was too small to perform a statistical analysis of the results from the questionnaire.

*Muscle contraction*

Electromyographic (EMG) electrodes were attached epidermally over the anterior tibial muscle and over the medial gastrocnemius muscle. The electrodes used in the study were Blue Sensor, Medicotest. The patients were instructed to activate both the anterior tibial muscle and the medial gastrocnemius muscle simultaneously to a sub-maximal (as much as they could) level possible to contract for about 20 seconds. To guide the patient's activity the EMG signals were visualised as bars on a computer screen, and the magnitude of the signal was recorded. After some practice all patients were able to activate both muscles simultaneously.

*Measurement of stump and socket volumes*

A black dot (6x6mm) was used as a reference marker, placed on the middle of ligamentum patellae prior to the scanning. The patients' relaxed amputation stumps were scanned with a CAPOD laser scanner, and the stump volume from ligamentum patellae to the distal stump end was calculated. After the first scanning, the patient was asked to activate the muscles to the previously stored EMG magnitude, and a new scanning was performed while the muscles were contracted. Each scanning was completed in 10 seconds. Volume calculations from both scans were carried out and compared. The same procedure was performed with a silicone liner donned and with the EMG electrodes still in place. Positive moulds of all patients' prosthetic sockets were produced, and the volumes of these prosthetic sockets were calculated with the CAPOD System. A comparison between the volume of the socket and the volume of the stump with the silicone liner donned was then performed.

*Statistical methods*

Means, ranges, standard deviations and student $t$-values were calculated according to standard procedures (Armitage and Berry, 1987). The power of the study was calculated both *a priori* and *post-hoc* with the software GPower (Faul and Erdfelder, 1992).

## Results

A limited number of the 168 variables from the questionnaire are described in Table 1. Fourteen (14) of 16 patients were satisfied with the comfort of the prosthesis moderately or better. None of the patients had any wounds on the amputation stump at the time of the study. None of the patients had constant stump pain but

Table 1. Patients satisfaction and use of prosthesis.

| Patient | Comfort of prosthesis (Satisfied) | Appearance of gait (Satisfied) | Wear of prosthesis (days/week) | Hours a day |
|---|---|---|---|---|
| 1 | Q | M | 7 | 14 |
| 2 | Q | Q | 7 | 11 |
| 3 | C | C | 7 | 16 |
| 4 | M | Q | 7 | 8 |
| 5 | S | S | 7 | 16 |
| 6 | C | M | 7 | 14 |
| 7 | Q | Q | 5 | 4 |
| 8 | C | S | 7 | 16 |
| 9 | M | M | 7 | 14 |
| 10 | M | N | 7 | 12 |
| 11 | Q | S | 7 | 5 |
| 12 | S | Q | 2 | 2 |
| 13 | C | C | 7 | 16 |
| 14 | Q | S | 7 | 2 |
| 15 | C | C | 7 | 12 |
| 16 | Q | M | 7 | 14 |

C=Completely, Q=Quite well, M=Moderately, S=Slightly, N=Not at all

9 of the patients experienced phantom pain. For 4 patients, during gait, the phantom pain increased but for 1 it decreased. Seven (7) patients experienced increased stump perspiration with the silicone liner donned. None of the above results have been statistically evaluated. The results from the measurements of volume changes, with and without a silicone liner, during muscle contraction yielded a *post-hoc* power of 0.82 ($\alpha$=0.05). Fourteen (14) of the 16 amputation stumps increased in volume during muscle activity. The mean volume increase was 5.8% (SD 5.3; range -4.2-14.2%) during muscle contraction in the amputation stump (Fig. 1). This increase was statistically significant ($p<0.001$). Stump volume, with contracted stump muscles and the silicone liner donned, increased for 13 of the 16 amputees. The mean volume increase was 3.5% (SD 3.3; range -1.4-11.5%) (Fig. 1). This increase was statistically significant ($p<0.001$). The mean difference between the socket volume of the

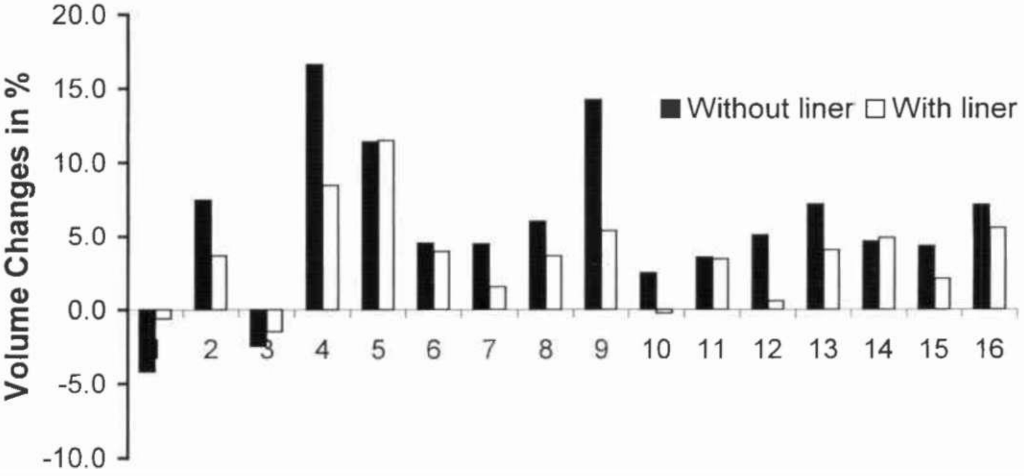


Fig. 1. Volume changes in per cent of relaxed and contracted stump both with and without silicone liner.

amputee's prosthesis and the stump volume was, for the relaxed stump, 1.8% (SD 10.1; range -15.3-18.7%). This difference was not statistically significant. The corresponding figures with the stump muscles contracted were -1.7% (SD 11.3; range -25.1-14.1%) (Fig. 2). This difference was not statistically significant.

## Discussion

The primary focus of this study was to examine differences in volume between a relaxed trans-tibial amputation stump and the same stump with the muscles contracted. The study was performed on trans-tibial amputation stumps with a silicone liner donned as well as without any liner. A significant increase was found in volume when the patients contracted the stump muscles compared to that of the relaxed stump, both with and without the silicone liner (Fig. 1). The increase in volume of the stump without a silicone liner approximately equals the volume of 1 terry cloth stocking. However, a comparison between the volume of the prosthetic socket and the stump volume, with the silicone liner, did not show any significant differences (Fig. 2).

It has been common practice to consider the amputation stump, inside the prosthetic socket as a closed hydrostatic system filled with a non-compressible fluid. If this were true, an increase in the cross-sectional area of some part of the system must necessarily be associated with a corresponding reduction somewhere else. This model, however, is not accurate. First of all, the socket is not closed, but open at its upper end. Secondly, the soft tissues do not behave as a non-compressible fluid. Not only the passive properties of these tissues must be considered, but also the biological changes associated with muscle activity. In a state of rest, the muscles are relatively sparsely perfused with blood. At the capillary level, blood is circulating through a relatively coarse metarteriole (preferential channel) which is directly connected to the venous return, and relatively few capillaries are open. At full activity, circulation in the muscle tissue can increase by a factor of 20. This is achieved by the opening of vascular sphincters at the transition between arteriole and capillary. This increase in capillary circulation increases the volume of the soft tissue as well as, probably, the leakage of vascular fluid into the extravascular tissues. Furthermore, during muscle activity, waste products, for example lactate, and other metabolic products accumulate in the muscle. These substances have an osmotic activity. If these substances are not effectively flushed out of the tissues, they will bind water and contribute to a further increase in volume of the soft tissues (Guyton and Hall, 1996).

Muscular activity in the lower limb of trans-tibial amputees during gait has been investigated with electromyography by several authors

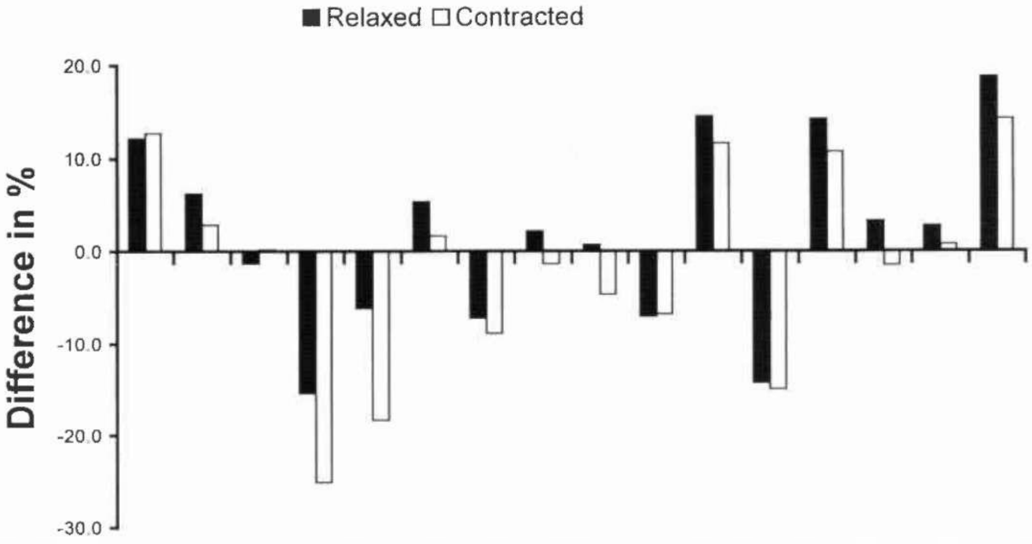


Fig. 2. Differences in per cent between the prosthetic socket and the stump with a silicone liner. Compared both with relaxed and contracted stump muscles.

(Winter and Sienko, 1988; Culham *et al.*, 1986; Grevsten and Stålberg, 1975; Burgess *et al.*, 1974). However, only Grevesten and Stålberg (1975) analysed the activity of the amputation stump muscles while the other authors investigated the thigh muscles of trans-tibial amputees. Among patients with a trans-tibial amputation, fitted with a PTB prosthesis, Grevsten and Stålberg (1975) found a simultaneous contraction of the anterior tibial muscle and the gastrocnemius muscle when the load on the prosthesis was largest. The muscular activity is closely related to the different phases of the gait cycle, and among amputees it may contribute to the fit of the socket (Burgess *et al.*, 1974; Lilja and Öberg, 1998). The present study focuses on volume changes of the stump when the muscles of the stump are activated.

In trans-tibial amputees, as well as among non-amputees, the maximum ground reaction forces during gait exceed 100% of the body weight (Winter and Sienko, 1988; Hermodsson *et al.*, 1994; Hubbard and McElroy, 1994). These forces have to be transferred from the prosthetic socket to the amputation stump and further to the skeleton. The possibility of transferring these forces is influenced both by the biomechancial properties of the amputation stump and the physical properties of the prosthetic liner (Silver-Thorn and Childress, 1996). The soft tissues of the stump have quasi-linear viscoelastic properties with respect to stress and strain while the soft socket liner has properties related to its specific material (Sonck *et al.*, 1970; Fung, 1993; Silver-Thorn and Childress, 1996). These factors increase the complexity of force transmission.

The mechanical relationship between the stump and the socket is utilised to form a coupling, which is able to transfer the ground reaction forces from the prosthesis to the skeleton. The efficiency of this coupling depends on its inherent stiffness. The difference between the volume of the socket and the momentary volume of the stump is an important factor that contributes to regulation of the internal pressure inside the stump. Increased internal pressure results in increased stiffness of the coupling. One consequence of an unsatisfactory coupling (i.e. a coupling with low stiffness) is increased tibial displacement during gait resulting in a loss of energy and influence on proprioception and kinesthesis (Lilja and Johansson, 1993; Grevsten and Eriksson, 1975). Equally important as volume control is the shape of the socket. It is essential to have a high congruity between the socket and the stump, so-called surface matching, especially for non-voluminous amputation stumps with bony prominences. The primary aim of surface matching is to avoid tissue damage due to localised pressure peaks over prominent bony areas (Buis, 1997). Bader and Chase (1993) discussed the mechanics of the patient-orthosis interface, but similar discussions can be applied to prosthetics. They pointed out that tangential forces combined with normal forces increase the risk of obliteration of capillary blood flow. This emphasises the importance of a properly fitted prosthesis and knowledge about volume changes stressed in the present study.

If the prosthetic socket is fitted and the difference in volume between the prosthetic socket and the amputation stump is minimised when the stump muscles are relaxed, the internal pressure of the soft tissues increases as the muscles contract due to the restricted expansion of the stump volume. This results in increased stiffness of the stump-socket coupling. However, the opposite will occur if the volume difference is minimised when the stump muscles are contracted. Then the stiffness in the coupling will decrease as the stump muscles relax, and an inferior suspension of the prosthesis will be the result. When prostheses are fitted without soft-liners the consequences of muscle contraction are more pronounced, with the stiffness curve showing a steeper slope. However, if a thin soft-liner is used between the socket and the stump, the increased stump volume during muscle activity is compensated for through compression of the liner, and the stiffness curve will increase more slowly as muscles contract. At the same time the patient will experience a moderate increase in the stiffness of the coupling between the amputation stump and the prosthetic socket and a tightening of the fitted socket. The present study indicates an increase in stump volume of about 5% when contracting the stump muscles, and many prosthetists have probably experienced the problem with a well-fitted socket as the patient complains about the socket being too tight during gait. This might be the result of an overly tight fitting of the socket, increased pressure inside the stump and an excessively increased stiffness in the coupling between the stump and the socket during muscle activity.

In the authors' opinion, there are difficulties in controlling the stump shape and stump volume using traditional techniques, including hand casting and rectification. One possibility to increase this control is by use of CAD/CAM techniques (Brüssel, 1991; Lilja and Öberg, 1995; Johansson and Öberg, 1998). All CAD/CAM software includes an option for the determination of the volume of the stump and modification of the positive model. In addition, the use of pressurised casting might, however, offer increased possibilities to control the stump volume during the production of a prosthetic socket (Murdoch, 1968).

In the present study, 16 trans-tibial amputees participated. Even if the number of patients was relatively low, a *post-hoc* calculation of power with GPower (Faul and Erdfelder, 1992), yielded a power of 0.82 ($\alpha$=0.05), indicating a sufficient number of patients for the study. As 14 of 16 patients considered comfort of the prosthesis to be average or better, the fit of the prosthetic socket was good, from the patient's point of view. However, a comparison of the volume of the socket and the stump volume with the silicone liner donned showed considerable differences in volume (Fig. 2). For 1 patient included in the study, the volume difference between the prosthetic socket and the amputation stump was as high as 18% and the patient still considered the comfort to be good. These results indicate that there are variables other than mere volume differences that influence the results of prosthetic fitting. Breakey (1997) studied some psychological aspects of prosthetic fitting, especially the body image using the amputee body image scale. These different psychological aspects of prosthetic fitting probably coincide with other objective variables such as volume and shape.

Differences in amputation technique among the participants in the study, with 3 patients amputated with sagittal technique and 13 patients amputated with a long posterior flap, might have had adverse effects on the results but, in this study, the patient was used as his own control.

The results of the present study are naturally related to the patients' ability to contract the stump muscles. All patients trained their ability to contract the muscles before the first measurement. However, if a patient could not make a maximal contraction due to inability to co-ordinate the muscle activity, the volume changes can only increase as the amputee's ability to activate the muscles increases. An increase in ability to contract the muscles will result in an increase in stump volume. The observed volume changes in the present study can be related to the volume of 1 terry cloth sock, with a volume of approximately 5% (Lilja and Öberg, 1977). This can then be used as a compensation for a discrepancy between the socket volume and the stump volume.

As the profession of prosthetics aims toward a more academic standing, there is an increased need for a theoretical foundation for clinical practices. Today, there remain several areas with a lack of basic theoretical knowledge. According to Pike (1996), there might be a revolution coming to the field of prosthetics and the prosthetists of today have to be prepared. However, the present knowledge of handicraft in the profession is comprehensive, but it has to be supported by a theoretical base. The results of this study may contribute to the theoretical base needed for the future education of prosthetists/orthotists. Prosthetists can implement the results from the present study into their clinical work.

## Conclusions

This study had identified and documented trans-tibial volume changes during muscle contraction of the anterior tibial muscle and the medial gastrocnemius muscle. There was a significant increase in stump volume of 5.8% during muscle contraction. With an ICEROSS silicone liner donned, the volume increased significantly by 3.5%.

The results indicate the importance of making a hand cast with the stump muscles relaxed if the subject is to have a stiff coupling between the amputation stump and the prosthetic socket during the stance phase of gait.

## Acknowledgement

This study was supported by grants from the Scientific Committee of the Jönköping County Council.

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