JRRD Volume 42, Number 5, Pages 635–644
September/October 2005
Journal of Rehabilitation Research & Development

# A multicriteria decision analysis of augmentative treatment of upper limbs in persons with tetraplegia

**J. M. Marjan Hummel, PhD;[1*] Govert J. Snoek, MD;[2–3] Janine A. van Til, MSc;[2] Wouter van Rossum, PhD;[1] Maarten J. IJzerman, Prof PhD[2]**

*[1]Faculty of Business, Public Administration and Technology, University of Twente, Enschede, the Netherlands; [2]Roessingh Research and Development, Enschede, the Netherlands; [3]Roessingh Rehabilitation Centre, Enschede, the Netherlands.*

**Abstract—**This study supported the evaluation by a rehabilitation team of the performance of two treatment options that improve the arm-hand function in subjects with sixth cervical vertebra (C6) level Motor Group 2 tetraplegia. The analytic hierarchy process, a technique for multicriteria decision analysis, was used by a rehabilitation team and potential recipients to quantitatively compare a new technology, Functional Electrical Stimulation (FES), with conventional surgery. Performance was measured by functional improvement, treatment load, risks, user-friendliness, and social outcomes. Functional improvement after FES was considered better than that after conventional surgery. However, the rehabilitation team's overall rating for conventional surgery was slightly higher than that for FES (57% vs 44%). Compared with the rehabilitation team, potential recipients gave greater weight to burden of treatment and less weight to functional improvement. This study shows that evaluation of new technology must be more comprehensive than the evaluation of functional improvement alone, and that patient preferences may differ from those of the rehabilitation team.

**Key words:** analytic hierarchy process, decision analysis, Functional Electrical Stimulation, group decision support, hand function therapy, performance, reconstructive surgery, rehabilitation team, shared decision making, tetraplegia.

## INTRODUCTION

The field of rehabilitation has become increasingly complex. The demand for rehabilitation treatment increases, but the resources for rehabilitation are scarce. The allocation of rehabilitation resources to potential recipients is also often complex and many factors must be considered. One specific decision that must be made is how to allocate the appropriate assistive technology to potential recipients—the multidisciplinary nature of rehabilitation requires that the various rehabilitation professionals decided this as a team. Such teams include physicians, nurses, and members of different therapy services [1]. All parties involved must carefully consider the various factors that underlie the acceptance of the technology by the recipient [2].

This study focuses on a multicriteria decision method to support the evaluation of the importance of treatment characteristics and the performance of various different treatment approaches in a specific clinical situation. In the present study, a rehabilitation team and a group of potential

**Abbreviations:** AHP = analytic hierarchy process, ANOVA = analysis of variance, C5 = fifth cervical vertebra, C6 = sixth cervical vertebra, FES = Functional Electrical Stimulation, SCI = spinal cord injury, UL = upper limb.

**This material was unfunded at the time of manuscript preparation.**

*Address all correspondence to J. M. Hummel, PhD; University of Twente, Faculty of Business, Public Administration and Technology, Department of Health Care and Management, PO Box 217, 7500 AE Enschede, the Netherlands; +31-53-489-3340; fax: +31-53-489-2159. Email: j.m.hummel@sms.utwente.nl

DOI: 10.1682/JRRD.2004.07.0088

recipients with sixth cervical vertebra (C6) level tetraplegia evaluated the importance of the treatment characteristics of reconstructive interventions of the upper limbs (ULs). The rehabilitation team evaluated the performance of two different interventions for the ULs for subjects with C6-level tetraplegia based on the treatment characteristics.

In individuals with tetraplegia due to a cervical spinal cord injury (SCI), the motor level relates to the level of independence in the activities of daily living [3–5]. Therefore, therapy of the ULs is very important. For subjects who meet the selection criteria, reconstructive surgery of the ULs can partially restore elbow extension and grasp function [6–8]. More recently, the implantation of Functional Electrical Stimulation (FES) devices has been introduced to improve UL function. In the FES system (Freehand System™*), electrodes are surgically placed onto the paralyzed hand muscles that are responsible for grasp and release. These electrodes are connected to a subcutaneous receiver-stimulation unit, which interprets voluntary signals from motions such as shoulder elevations, and transfers the appropriate stimulation waveforms via the electrodes to the target muscles. Physicians usually combine FES implants with conventional surgical procedures to optimize patients' functional abilities [9–10].

To judge eligibility for surgery, physicians classify patients according to the International Classification of the Upper Limb in Tetraplegia [11–12]. This classification scores the number of functional muscles below the level of the elbow with a strength grade of at least 4/5, with the use of a manual muscle test. The muscles are classified into nine separate motor groups (Groups 0 to 9). In addition to motor function, sensory function is also tested with the two-point discrimination test of the pulp of the thumb. Subjects classified as Motor Group 0 have no muscle below the elbow with a strength of Grade 4/5, so FES is the only option to enhance hand function. For those classified as Motor Group 1, only the musculus (m.) brachio radialis has a strength of grade 4/5, and for Motor Group 2, both this muscle and the m. extensor carpi radialis longus have a strength of grade 4/5. In subjects classified as Motor Group 3, the m. extensor carpi radialis brevis also has a strength of grade 4/5, and for Motor Groups 4 to 9, more muscles per group have this minimum strength.

For subjects with fifth cervical vertebra (C5) lesions in Motor Group 1 and especially for subjects with C6 lesions in Motor Group 2, limited surgical procedures, as well as reconstructive surgery combined with FES implants, can be considered. These subjects have to choose between these two treatment options if they are willing to undergo a reconstructive procedure. To support their decision, subjects will ask their rehabilitation teams for advice. In order to be able to give the correct advice, the teams must clearly understand and be able to explain their preferences for the treatment options.

Decision making by rehabilitation teams is likely to be negatively influenced by a lack of time, a lack of procedural guidelines, the disregard of alternative opinions, and a team member or leader dominating the process [1]. Teams will benefit by developing strategies to enhance their teamwork and developing guidelines to standardize their decision processes. The analytic hierarchy process (AHP), a technique developed by Saaty for multicriteria decision analysis that supports team decision making [13] can help rehabilitation treatment teams evaluate the performance of new medical technology. The aim of this study was to support, with the AHP, the evaluation by a rehabilitation team of conventional UL reconstructive surgery and reconstructive surgery combined with FES. An additional component of this study compared the treatment requirement preferences of a group of potential recipients of reconstructive interventions with the preferences of a rehabilitation team.

## MATERIALS AND METHODS

A decision is a choice between two or more alternatives, and the choice for an alternative is generally based on multiple criteria or requirements. Saaty's AHP is a technique for multicriteria decision analysis [13]. This technique supports decision makers, both individual and group, when they have to choose between alternatives. The AHP structures group discussions, emphasizes any disagreements among group members, and supports a quantitative comparison between the alternatives. It helps to quantitatively estimate how well the alternatives fulfill a number of performance requirements, which themselves

*The Freehand System was developed by the Cleveland FES Center, Departments of Orthopedics and Biomedical Engineering, Case Western Reserve University, Cleveland Department of Veterans Affairs Medical Center, and MetroHealth Medical Center, Cleveland, OH, USA. It was previously available from The Neuro Control Corporation, 8333 Rockside Road, Valley View, OH 44125, USA. As of 2003, that corporation has stopped delivery of the system and to date no other firm has resumed this activity.

can be both quantitative and qualitative [13]. The AHP has been implemented in a group decision support system software called "Team Expert Choice."*

We applied the AHP to evaluate the effectiveness of FES in enhancing the hand function of subjects with C6-level tetraplegia. An expert panel compared the effectiveness of surgery including an FES implant with conventional surgery for a specific group of potential recipients. These recipients were subjects with C6-level tetraplegia who were classified as Motor Group 2 according to the International Classification of the Upper Limb in Tetraplegia. The recipients can keep sufficient balance, are psychologically adjusted to their injury, can learn to use the revised hand function, and have target muscles that can be stimulated by electrical waveforms. These subjects can undergo conventional surgery to improve elbow extension (posterior deltoid to triceps transfer).

To improve the hand function of these subjects, a physician could consider both conventional surgery and reconstructive surgery combined with an FES. Conventional surgery is the active transfer of the m. brachioradialis to thumb or finger flexors, which can be eventually combined with tenodesis of thumb or finger flexors. This therapy results in one active and one tenodesis grasp of either palmar or lateral grasp. Surgery combined with an FES implant results in a stimulated lateral and palmar grasp function. An extensive review of the possibilities can be found in the literature [6–10].

The expert panel included two rehabilitation physicians, two occupational therapists, two physiotherapists, and one social worker, as well as a person with C6 complete tetraplegia. These panel members were selected on the basis of their knowledge about the treatment of the tetraplegic arm-hand or the psychosocial effects involved. All professional members belonged to the same SCI treatment team and had considerable experience (between 8 and 24 years) treating patients with SCI and a special interest and expertise in the treatment of ULs. The person with tetraplegia had sustained his injury over 20 years ago, has undergone reconstructive UL surgery, and is active as a counselor for people who have recently sustained an SCI. A nurse on this team was unable to attend the evaluation.

The panel members were seated at a U-shaped table facing a facilitator. Hardware consisted of a laptop on which Team Expert Choice was installed, a projection system, a radio frequency receiver, and individual wireless keypads for the panel members. Panel members first defined the appropriate group of potential recipients, FES, and reconstructive surgery. A 10 min brainstorming session followed, in which the panel members formulated performance requirements for assessing the treatment options, then read them out to the panel. The facilitator entered these requirements in Team Expert Choice and projected them on a screen, such as shown in this example:

> In the present study, the objective is to choose, out of two alternative arm-hand treatments, the treatment with the highest performance. Some of the main performance requirements are, for example, safety of the treatment, influence on the quality of the hand function, and ease of using the hand.

In the next step, each of the main requirements was divided into several subrequirements. The panel discussed all requirements to ensure that the main requirements, as well as each group of subrequirements, were mutually exclusive, clear, comprehensive, and of importance within the same order of magnitude. These requirements were revised until the panel had no further comments, additions, modifications, or omissions.

The expert panel members then compared the importance of the requirements. First, they compared the importance of each pair of two main requirements on a nine-point scale, on which a score of 1 indicated equal importance of the requirements. If the panel considered one of the requirements to be more important than the other, it assigned that requirement a score ranging from 2 to 9, depending on the level of importance. An example of a pairwise comparison of the importance of two main requirements follows:

> Which requirement is more important with regard to the performance of the hand treatment, and to what degree?
>
> Safety is a requirement that is—
>
> (1) equally, (3) slightly more, (5) strongly more, (7) very much more, (9) exceedingly more important than the quality of the hand function.
>
> [2, 4, 6, and 8 represent intermediate values]

Then the panel compared the importance of each pair of subrequirements that related to the same main requirement. Likewise, they compared the performances of the two treatment options with regard to each subrequirement.

*Team Expert Choice 2000 is commercially available at Expert Choice, Inc., 5001 Baum Boulevard, Suite 650, Pittsburgh, PA 15213, USA. System requirements: 32 multibank dynamic random-access memory, Pentium central processing unit, and Windows 95, 98, Me, NT4, 2000, or XP.

In this case, the comparison focused on which treatment option was preferred with regard to the subrequirement and to what degree. For the comparisons between treatments, the 9-point scale ranges from indifference to extreme preference.

Using their handheld radiographic keypads, the panel members gave their scores for each pairwise comparison. Individual scores were projected on a screen, which enabled the panel members to discuss their scores. During the discussions, the panel members could alter their scores. No actual consensus was forced. Group scores were the geometric averages of the final individual scores for the pairwise comparisons.

The AHP software uses the group scores for the pairwise comparisons to calculate the weighting factors according to an eigenvector method. This eigenvector method can be interpreted as a simple averaging process, by which the weights are the average of all possible ways of comparing the importance of the requirements or the preference for the treatments. Accordingly, the weights that were calculated represent the relative importance of the main and subrequirements and the relative preference for the treatments with regard to each subrequirement. These weights were used to calculate an overall weighted preference for the two treatment alternatives. (Saaty and Vargas [14] and Hummel [15] give more in-depth explanations of this mathematical approach.) The software illustrates these weights using graphs, but a sample description of this calculation follows:

> For example, two decision makers are convinced that safety and ease of use are equally important (score = 1), and two other decision makers consider safety to be much more important than ease of use (score = 5). The group score is therefore 3, indicating that safety is slightly more important than ease of use. Let us assume further that the safety of treatment 1 is preferred slightly more than the safety of treatment 2. On the other hand, treatment 2 is preferred slightly more than treatment 1 with respect to the ease of using the hand. The treatments are equally preferable with respect to their influence on the quality of the hand function. In this example, treatment 1 is safer than treatment 2, but the hand will be more difficult to use. Since safety is weighted stronger in this evaluation than ease of use, the results indicate that treatment 1 is preferred. Overall, this treatment is therefore considered to perform better than treatment 2.

An additional exploratory study was performed to investigate whether the results obtained during the session with the rehabilitation team were in accordance with the needs of potential recipients. In other words, do potential recipients have the same values as the rehabilitation team with regard to the requirements of surgery combined with FES and conventional surgery? Eight rehabilitation centers specializing in SCI care in the Netherlands selected 34 persons with C6-level tetraplegia to participate in this formal study. Criteria for the inclusion of subjects were that they have C6-level Motor Group 2 cervical SCI, that the time since their injury was >1 year (stable neurological condition), and that they were not recently informed about reconstructive surgery. Patients were excluded if they had either received reconstructive surgery or had declined treatment within the previous year. The subjects were individually interviewed by a research assistant and asked to assess, pairwise, the relative importance of each pair of the main requirements that had been defined by the expert panel. The subjects made a total of 10 pairwise comparisons. Because this study was combined with other questionnaires, the available time was limited, so subjects were not asked to value the subrequirements. We performed an analysis of variance (ANOVA) to compare the importance of each main requirement, as rated by the members of the expert panel ($n$ = 8) and the potential recipients ($n$ = 34). This additional study involving subjects with SCI was approved by the Roessingh Rehabilitation Centre Ethical Committee (Enschede, the Netherlands).

## RESULTS

In the evaluation of reconstructive surgery including an FES implant compared with conventional surgery, the expert panel considered 19 subrequirements to be relevant. These requirements were related to five main requirements: ease of use, social acceptance, improved arm-hand function, minimal risks, and minimal load of the treatment (**Figure 1**).

**Figure 1** and the **Table** show detailed quantitative results of the weighting according to the expert panel. **Figure 1** shows the weighting factors in parentheses of the main requirements and the subrequirements. These weighting factors represent the relative importance of these requirements according to the panel. The **Table** shows weighted factors of the panel's preferences for the two treatment options for each subrequirement separately.

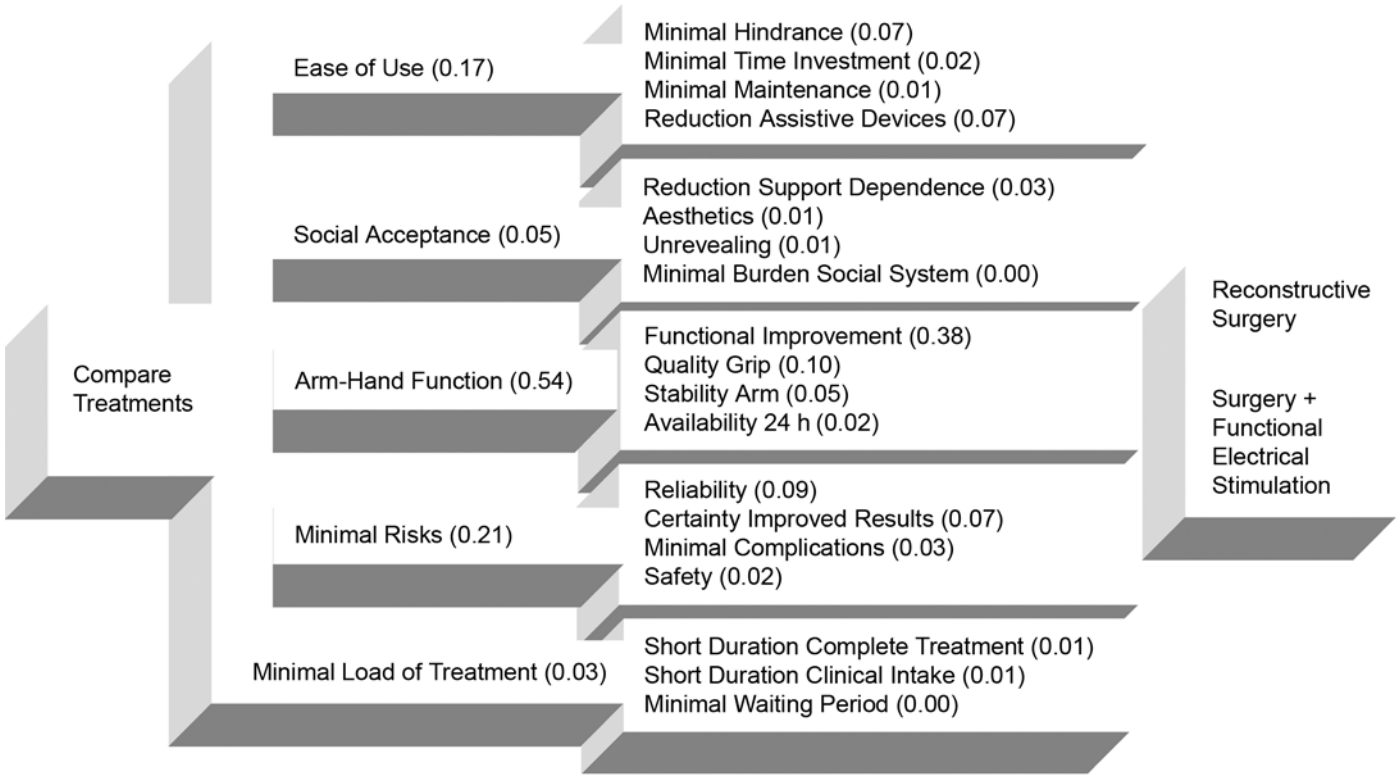


**Figure 1.**
Evaluation structure with weighting of subrequirements by expert panel.

A high weight indicates a strong preference of the expert panel for the effectiveness of the specific treatment option in fulfilling the corresponding subrequirement.

In summary, the most important main requirements associated with a treatment option, according to the rehabilitation team on our expert panel, are functional arm-hand results (0.54), risks (0.21), and ease of use (0.17). In general, surgery combined with FES is preferred for its improvement of the arm-hand function. For example, the quality of the grip is considered to be superior if treated by FES. In contrast, conventional surgery without the implantation of an FES device scores better on most of the remaining subrequirements. For example, after surgery the improved hand function is available 24 hours a day, hinders the person with tetraplegia less, can be used in less time, requires less maintenance, and is less revealing.

**Figure 2** shows an overview of the expert panel's final weighting factors of the main requirements (gray bars), the weighted preferences for the treatments in fulfilling these requirements (dashed and solid lines), and the overall weighted preference for the treatments (ends of lines). The overall preference of the panel was 44 percent for surgery combined with FES versus 56 percent for conventional surgery. The panel preferred surgery combined with FES for its improvement of the arm-hand function, and this improvement is considered to be the most important requirement. Nevertheless, the overall (average-weighted) preference for conventional surgery is slightly higher than the preference for surgery with FES. This overall preference for conventional surgery is explained by, in order of decreasing influence on the overall outcomes, the greater ease of use of the arm-hand function after surgery, the lower risks involved, the greater social acceptance, and the lesser load of reconstructive surgery. An important determinant of less ease of use after surgery with FES is that the FES system may hinder the person with tetraplegia. The FES equipment has to be put on and taken off each day and must be transported during the day. An important cause of the higher risks involved in the FES treatment is that, in addition to the normal complications of reconstructive surgery, failure of the FES system may necessitate surgical

**Table.**
Relative weighting of subrequirements by expert panel.

| Subrequirement | Functional Electrical Stimulation | Surgery |
|---|---|---|
| Ease of Use | | |
| Hindrance | 0.12 | 0.89 |
| Time Investment | 0.11 | 0.89 |
| Maintenance | 0.11 | 0.89 |
| Assistive Devices | 0.46 | 0.54 |
| Social Acceptance | | |
| Dependence | 0.38 | 0.62 |
| Aesthetics | 0.12 | 0.88 |
| Unrevealing | 0.11 | 0.89 |
| Social Burden | 0.16 | 0.84 |
| Arm-Hand Function | | |
| Functional | 0.52 | 0.48 |
| Quality Grip | 0.78 | 0.22 |
| Stability Arm | 0.50 | 0.50 |
| Availability | 0.10 | 0.90 |
| Minimal Risks | | |
| Reliability | 0.18 | 0.82 |
| Certainty Results | 0.48 | 0.52 |
| Complications | 0.15 | 0.85 |
| Safety | 0.34 | 0.66 |
| Minimal Load of Treatment | | |
| Duration Treatment | 0.33 | 0.67 |
| Duration Intake | 0.52 | 0.48 |
| Waiting Period | 0.31 | 0.69 |

repair and the implanted parts may become infected and subsequently have to be removed [10].

In the additional component of our study, 34 potential recipients rated the importance of the main requirements. **Figure 3** shows the mean scores for importance of the main requirements as rated by the expert panel and the 34 potential recipients. The ranges of the importance scores for importance in both groups are also indicated in **Figure 3**. An ANOVA showed that the means of the scores for importance differ significantly between the two groups for improvement of the arm-hand function ($p = 0.005$) and load of the treatment ($p = 0.01$). However, substitution of the expert panel scores for importance with the recipient scores for importance would not change the mean overall preference to surgery combined with FES rather than conventional surgery. Each recipient would have a slight preference for conventional surgery.

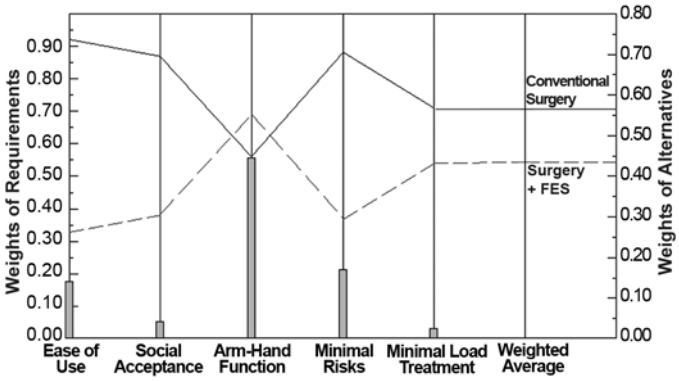


**Figure 2.**
Expert panel's weighting of main requirements (bars) and preferences for surgery with Functional Electrical Stimulation (dashed line) and conventional surgery (solid line).

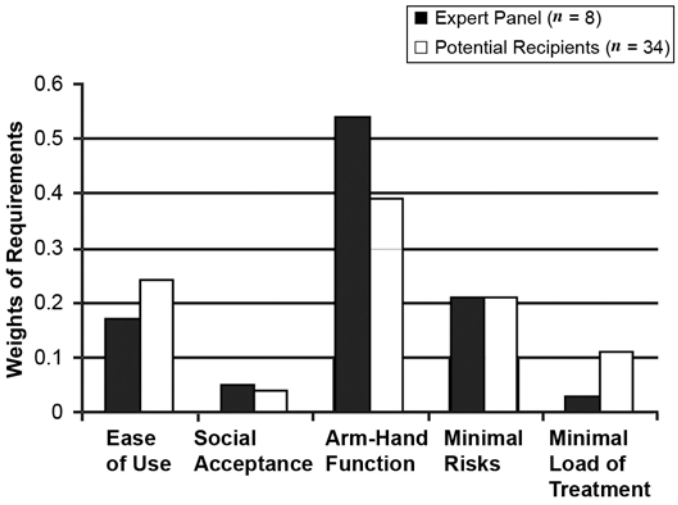


**Figure 3.**
Comparison of weighting of main requirements by expert panel and potential recipients.

## DISCUSSION

Clinical trials about the application of new treatment technology generally focus only on the functional effects and/or safety of the new technology. However, besides functional outcome and safety, one must consider more treatment characteristics in the evaluation of the performance of the treatment. A lack of knowledge about the performance in all aspects of assistive technology may result in the inappropriate allocation of treatment, which is likely to decrease patient satisfaction and increase the costs of healthcare.

In the present study, an experienced rehabilitation team in the field of UL treatment for tetraplegia and a person with tetraplegia compared the performance of reconstructive surgery with FES with the performance of conventional surgery for subjects with a specific tetraplegic condition. This multidisciplinary team formulated technical, medical, and social performance requirements. In more comprehensive panel evaluations, the amount of treatment options can be increased by adding, for example, the option of no medical intervention. But in this first evaluation, we included two comparable treatment options that question the difference in performance with regard to each of these performance requirements and therefore would benefit from an in-depth discussion about all these requirements. The systematic procedure offered by the AHP helps to prevent important deficiencies in team decision-making, such as failure to carry out all elements of the decision-making process, isolation from alternative opinions, and dominance. Although such evaluations are still likely to take several hours, particularly when controversial technology is introduced, such panel evaluations are important.

The results of laboratory-based assessments indicate that the FES system is able to enhance grasp and pinch better than conventional surgery [10]. In line with these results, the expert panel preferred surgical therapy combined with an FES implant above conventional surgery for its functional improvement of the arm-hand of C6-level Motor Group 2 persons with tetraplegia. However, the overall preference for surgery with FES is rated slightly lower than the preference for conventional surgery. This is because of the greater ability of conventional surgery to meet other requirements, in particular the ease of using the hand after surgery and the low risks involved in this treatment. Moreover, if actual recipients values had been considered, the balance would shift even more toward a preference for reconstructive surgery. This is supported by the experiences of the expert panel in rehabilitation practice. These results underline the need to evaluate rehabilitation technology more comprehensively and not just to simply evaluate functional performance of technology. Functional outcomes alone cannot predict the acceptability of or satisfaction with assistive technologies.

The opinions of users and professionals from a variety of disciplines are needed to determine all the relevant performance requirements. The panel, as a whole, needs to be a well-balanced representation of individuals with relevant, state-of-the-art knowledge about each of the domains of rehabilitation. Each panel member can contribute arguments that support the judgments in his or her specific domain. For example, the person with tetraplegia in the expert panel was not familiar with the performance of FES. However, he could contribute to the panel discussions in particular by explaining why certain performance requirements were more important than others.

The question remains whether a rehabilitation team should speak for the patient in defining the requirements of treatment options and their relative importance [16–17]. This question is raised because, compared with the potential recipients, the expert panel rated the load of the surgery combined with FES to be less important and functional improvement of the arm-hand function to be more important. This has also been observed in other studies [18–19]. The comparison between the outcomes of the panel and outcomes of the subjects with tetraplegia can only be considered an exploratory, pilot assessment. Even though the subjects with tetraplegia were supported by the AHP, they did not experience the panel discussions and they were not familiar with both types of treatment. To learn the opinions of potential recipients who have to choose a treatment, we included only potential recipients and not actual recipients of FES or conventional surgery. Bias in their opinions due to lack of experience is limited because they were asked only to rate the importance of the main requirements and not to judge the performance of the treatments. Furthermore, to facilitate our comparison of the two groups, we did not allow the potential recipients to select the main performance requirements, only the expert panel. Future research will compare the outcomes of the expert panel with the outcomes of actual recipients who have gained experience with the FES system or surgery to restore their arm-hand function.

## CONCLUSIONS

This study indicates that this specific rehabilitation treatment team had a slight preference for FES over conventional surgery when considering UL interventions for subjects with C6-level Motor Group 2 tetraplegia in a specific clinical setting. Before this evaluation, the panel members did not receive a meta-analysis of the literature on these treatment options. This evaluation was based on the panel's existing knowledge of the relevant literature and the multidisciplinary knowledge that has been acquired in the treatment of persons with C6-level tetraplegia in the

specific treatment facility. One should note that FES is a relatively new treatment option and so experience must still be gained. Growing experience, an increasing body of literature on the performance of this treatment, and improvements of the FES systems [20] may influence preferences for FES. According to our results, the impending improvement in the user-friendliness of the FES system is likely to be an important factor to increase preference for the FES system. In the early stages of clinical implementation, objective measurements of various aspects of the performance of new versus more established treatment options are limited. For future evaluations, the AHP offers the possibility to integrate the results of well-designed studies on the performance of various different treatment options on one or more of the performance requirements, such as UL function or complication risk. Because of these factors, the outcomes of this panel evaluation cannot be generalized to other treatment teams or other circumstances. The essence of such panel evaluations is to reveal and discuss the arguments that support the preference of a treatment team in its own specific circumstances. This particular preference shapes the advice given by treatment teams or individual caregivers to patients.

The outcomes can be used as guidance in sharing information with individual patients. The importance of the requirements and preferences for the treatments can subsequently be attuned to their specific needs and characteristics. Our results show that the individual potential recipients have a relatively wide range of opinions about the importance of the performance requirements. In a quick screening procedure for a specific patient, the minimal requirements of the treatment options can be discussed. In clinical practice, the option of no intervention at all should be included in this discussion. No intervention at all would be a disadvantage in the arm-hand function area, but would have advantages with regard to treatment load and risks. If a patient wants to be treated and a certain treatment option fails to meet the minimal requirements of this patient, that specific treatment option should no longer be considered. For instance, if a patient does not want to consider implanted devices at all, then surgery with FES implants does not need to be discussed. For a patient to choose between the acceptable treatment options, that patient and the rehabilitation team should discuss in detail the importance of the performance requirements for the patient and carefully compare the various treatment options.

Potential FES recipients, as well as rehabilitation professionals, lack knowledge about the various factors that underlie the acceptance of assistive technology [2]. Comprehensive evaluations of rehabilitation technology, such as described in this study, are designed to enhance this knowledge that rehabilitation professionals require to allocate the appropriate rehabilitation technology to potential recipients.

## REFERENCES

1. Unsworth CA, Thomas SA, Greenwood KM. Decision polarization among rehabilitation team recommendations concerning discharge housing for stroke patients. Int J Rehabil Res. 1997;20(1):51–69.
2. Triolo R, Nathan R, Handa Y, Keith M, Betz RR, Carroll S, Kantor C. Challenges to clinical deployment of upper limb neuroprostheses. J Rehabil Res Dev. 1996;33(2):111–22.
3. Long CI, Lawton EB. Functional significance of spinal cord lesion level. Arch Phys Med Rehabil. 1955;36(4):249–55.
4. Ditunno JF, Flanders AF, Kirschblum S, Graziani V, Tessler A. Predicting outcome in traumatic spinal cord injury. In: Kirschblum S, Campagnolo DI, DeLisa JA, editors. Spinal cord medicine. Philadelphia (PA): Lippincott Williams & Wilkins; 2002. p. 108–22.
5. Marino RJ, Rider-Foster D, Maissel G, Ditunno JF. Superiority of motor level over single neurological level in categorizing tetraplegia. Paraplegia. 1995;33(9):510–13.
6. Johnstone BR, Jordan CJ, Buntine JA. A review of surgical rehabilitation of the upper limb in quadriplegia. Paraplegia. 1988;26(5):317–39.
7. Keith MW, Lacey SH. Surgical rehabilitation of the tetraplegic upper extremity. J Neurol Rehabil. 1991;5(1):75–87.
8. Waters RL, Sie IH, Gellman H, Tognella M. Functional hand surgery following tetraplegia. Arch Phys Med Rehabil. 1996;77(1):86–94.
9. Keith MW, Kilgore KL, Peckham PH, Wuolle KS, Creasey G, Lemay M. Tendon transfers and functional electrical stimulation for restoration of hand function in spinal cord injury. J Hand Surg. 1996;21(1):89–99.
10. Peckham PH, Keith MW, Kilgore KL, Grill JH, Wuolle KS, Thrope GB, Gorman P, Hobby J, Mulcahey MJ, Carroll S, Hentz VR, Wiegner A, Implantable Neuroprosthesis Research Group. Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: A multicenter study. Arch Phys Med Rehabil. 2001;82(10):1380–88.
11. McDowell CL, Moberg EA, House JH. The second international conference on surgical rehabilitation of the upper limb in tetraplegia. J Hand Surg. 1986;11A:604–8.
12. Waters RL, Mucitelli LM. Tendon transfer to improve function of patients with tetraplegia. In: Kirschblum S, Campagnolo DI, DeLisa JA, editors. Spinal cord medicine. Philadelphia (PA): Lippincott Williams & Wilkins; 2002. p. 409–23.

13. Saaty TL. Group decision-making and the AHP. In: Golden BL, Wasil EA, Harker PT, editors. The analytic hierarchy process: applications and studies. Berlin (Germany): Springer-Verlag; 1989. p. 59–67.
14. Saaty TL, Vargas LG. Prediction, projection and forecasting: applications of the analytic hierarchy process in economics, finance, politics, games and sports. New York (NY): Springer; 1990.
15. Hummel JM. Supporting medical technology development with the analytic hierarchy process [dissertation]. Wageningen (the Netherlands): Ponsen & Looijen BV; 2001. p. 171–76.
16. Slevin ML, Plant H, Lynch D, Drinkwater J, Gregory WM. Who should measure quality of life, the doctor or the patient? Br J Cancer. 1988;57(1):109–12.
17. Dolan JG. Are patients capable of using the analytic hierarchy process and willing to use it to help make clinical decisions? Med Decis Making. 1995;15(1):76–80.
18. Suarez-Almazor ME, Conner-Spady B, Kendall CJ, Russell AS, Skeith K. Lack of congruence in the ratings of patients' health states by patients and their physicians. Med Decis Making. 2001;21(2):113–21.
19. Hudak PL, Clark JP, Hawker GA, Coyte PC, Mahomed NN, Kreder HJ, Wright JG. "You're perfect for the procedure! Why don't you want it?" Elderly arthritis patients' unwillingness to consider total joint arthroplasty surgery: a qualitative study. Med Decis Making. 2002;22(3):272–78.
20. Peckham PH, Kilgore KL, Keith MW, Bryden AM, Bhadra N, Montague FW. An advanced neuroprosthesis for restoration of hand and upper arm control using an implanted controller. J Hand Surg. 2002;27(2):265–76.

Submitted for publication July 29, 2004. Accepted in revised form March 18, 2005.