Prosthetics and Orthotics International, 1999, 23, 123–129

Improvement of control cable system of trans-humeral body-powered prostheses

I. KITAYAMA*, M. MATSUDA**, S. NAKAJIMA**, S. SAWAMURA**, H. NINOMIYA*** and H. FURUKAWA****

**The Hyogo Assistive Technology Research and Design Institute, Hyogo Rehabilitation Center, Kobe, Japan*
***Central Hospital, Hyogo Rehabilitation Center, Kobe, Japan*
****Kinki Gishi Co. Ltd., Kobe, Japan*
*****Faculty of Health Science, Kobe University School of Medicine, Kobe, Japan*

Abstract

For the purpose of improving the efficiency of a body-powered prosthesis, a control cable system was developed which uses a pulley and a cable housing which includes a highly slippery plastic liner. Improvements were also made to the harness. In this paper, the mechanism of these systems is firstly described and then, the results of a clinical evaluation test of a practical model is presented along with an efficiency evaluation by a testing instrument. For the design of each system, the material and size suitable for the conditions of cosmetic and general versatility were considered. The clinical test was performed on 12 subjects to prove the effectiveness of the system. This test procedure was repeated. These tests proved the effectiveness of the systems.

Introduction

A body-powered prosthesis with a terminal device, and an elbow joint is operated by using a body movement which is mainly produced by scapular motion. It is important to transfer the effect of the body action efficiently for improved prosthetic function. Where body action is transferred through a harness, an ordinary upper limb amputee may produce a cable excursion of about 100mm and a force of about 100N or more. A body-powered prosthesis becomes more effective when both excursion and force are used efficiently. For this purpose a force transfer mechanism using a pulley and a harness and utilising a housing containing a highly slippery plastic (UHMW) liner was developed (Fig. 1). As a result, the cable movement was more effectively used and the force was more efficiently transferred. The following are the details of the system and the results of evaluation.

Mechanisms

On a body-powered prosthesis, the cable excursion (L) and force (F) are obtained by transferring the action of the scapula and other trunk movements to a harness. These are then transferred to a cable to operate an elbow joint or a terminal device. Although F and L must be as large as possible, they are greatly influenced by the selection of the harness system and its fitting to the amputee. It follows then that the loss in

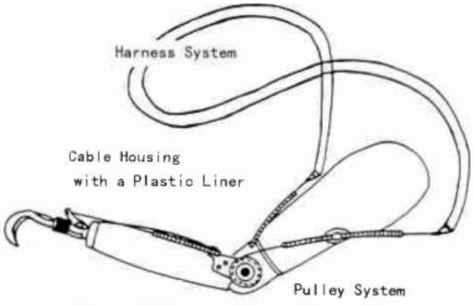

Fig. 1. Modified control cable system.

All correspondence to be addressed to Ichiro Kitayama, The Hyogo Assistive Technology Research and Design Institute, Hyogo Rehabilitation Center 1070, Akebono-cho, Nishi-ku, Kobe, 651-2181, Japan. Tel: (+81) 78-925-9283. Fax: (+81) 78-925-9284.

transferring F and L must be as small as possible. An explanation follows about a system developed for better force and excursion transfer.

The mechanism and design of a pulley system

In contrast with a method using a conventional forearm lift system (a lever system) for flexion of the elbow joint and the opening-closing of a terminal device, a pulley system is used with a cable reeled around a pulley which is attached to an elbow joint. The following study shows that the new system decreases the excursion of the cable necessary for elbow flexion. This is especially useful for high level upper limb amputees, who have less excursion capacity.

The operating principle of the system is as follows:

When the cable is pulled during the time the elbow is unlocked, the cable is reeled around a pulley to flex the elbow joint. When the cable is pulled after the elbow is locked, the pull is transferred through the pulley to open and close the hook. With these mechanisms, this method offers a function equivalent to a conventional dual controlled cable system. It also has the characteristics that only a very small loss of cable movement occurs in elbow flexion and the loss in transfer efficiency is minimal if the pulley rotates easily.

In order to be functional the pulley system is required to be of small bulk and as light as possible, with a low friction pulley and without friction at the cable, the system must also be stable in the transverse direction of the pulley, and durable. The basic specifications of the pulley and axle developed (Fig. 2) are:

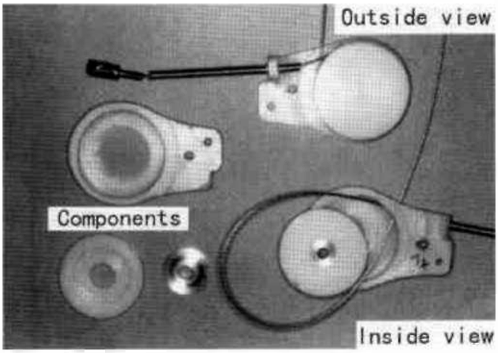

Fig. 2. Components and external appearance of the pulley system.

- the outside diameter of pulley = 38mm
- the inside diameter of pulley = 11mm
- the diameter of pulley groove = 35mm
- the thickness of pulley = 5mm
- material = high density polyethylene
- material of pulley axle = aluminium alloy
- weight = 7g (including the axle)

The following points were considered in developing a test model:

Because the pulley system is structured to be attached to the outside of the elbow joint, its volume must be as small as possible. However a pulley with a smaller diameter requires increased force to produce elbow flexion. With a prosthesis using an ordinary duralumin hook, the torque about the elbow axis is about 0.43Nm when the terminal device is not holding an object. With a 35mm outside diameter (17.5mm radius) of the pulley, the cable pull required for operation is calculated as 0.43/0.0175 i.e. about 25N theoretically when the pulley has no loss due to friction. With an outside diameter of 29mm a pull of about 30N is necessary for upper arm flexion. This means the smaller the diameter of the pulley the greater is the cable force requirement. Therefore, it is desirable to make the outer diameter as large as possible so that less force is required for the users. For comparison even Hosmer Corporation's 3/64 inch (1.19mm) cable needs an outside diameter of 32mm or more due to the minimum bending radius.

Another important factor about the design of pulley diameter is the controllability during the process of flexing the elbow to a desired angle. Amputees are required to operate the procedure swiftly by pulling a cable. If the excursion of the cable is inadequate, the angle of flexion hoped for cannot be achieved. In a pulley system as indicated, the cable force required is determined by the pulley diameter. In the above-mentioned 35mm pulley an excursion of about 41mm (35mm x π x 135 degrees $\div$ 360 degrees) is required for elbow flexion; a pulley with an outside diameter of 40mm requires 47mm excursion; a 30mm pulley requires 35mm. Preferably the diameter should be large from the viewpoint of operation only. But it cannot be unconditionally big because a bigger diameter results in a larger force requirement. Moreover, it must be noted that the elbow part gets bulky when the pulley has a bigger diameter.

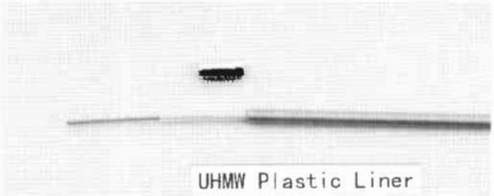

Fig. 3. Cable housing with a liner.

In summary, the pulley is preferably big for better operation of elbow flexion. Its outside diameter must be at least 35mm. A bigger pulley is also preferable for better control of elbow flexion. Its outside diameter must be 30mm at least. The pulley should be small so that the excursion can be kept to a minimum. The pulley is preferably smaller than 38mm for a better appearance. The outside diameter should be more than 32mm for the cable to have a sufficient bending radius.

In consideration of these points, the suitable external diameter of the pulley is between 32mm and 37mm. In this study the median of 35mm was adopted.

The pulley is preferably thin, but it must at least have the thickness to accommodate two grooves as wide as the cable diameter (Hosmer Corporation, 3/64 inch) plus the thickness of the groove wall. To satisfy these minimum requirements, the pulley was designed to be 5mm thick.

Cable housing with a liner (Fig. 3)

The housing has a highly slippery plastic liner within it. The present system had been marketed for heavier operations, but no liner usable for a cable housing with an ordinary diameter is available. So a liner was designed and produced which can be installed in a space between the outer rim of the 3/64 inch cable and the inner rim of an ordinary housing.

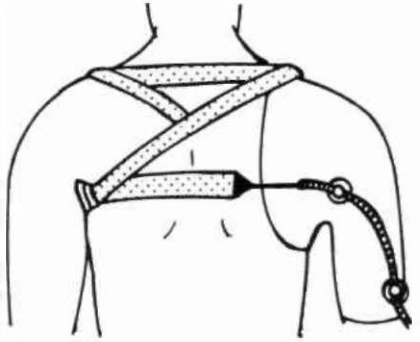

Fig. 4. Modified harness system.

Harness fitting

A body-powered prosthesis was used with a figure of 8-shaped harness. In the case of high level amputees or those with a less movable stump, an improved harness must be provided. The authors have had good results by adding either an elastic or non-elastic chest strap and by using a harness as shown in Figure 4.

Evaluation system

The test system shown in Figure 5 was

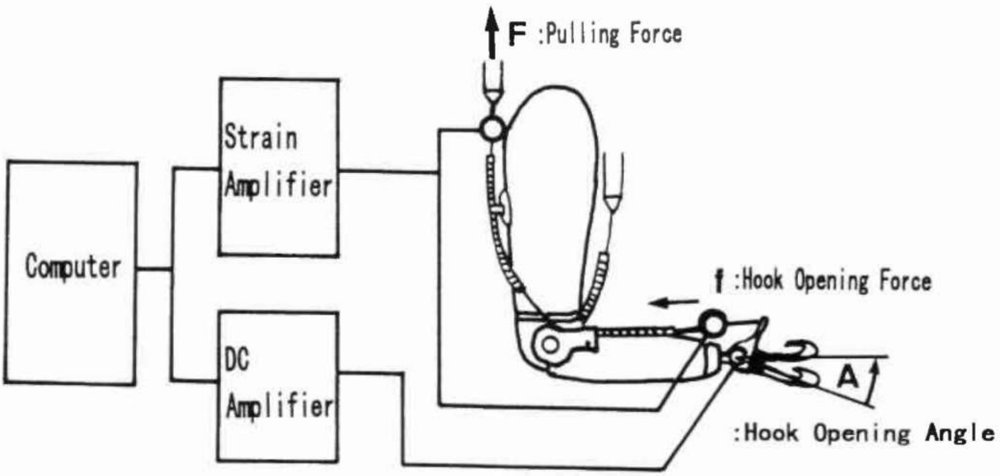

Fig. 5. Measuring system.
Pulling force, hook opening force and hook opening angle are measured.

manufactured to examine the operating capability of the prosthesis. It is designed to measure the hook angle with a goniometer and pulling force with an annular-shaped tensile sensor. Data from this system is transferred to a computer through an amplifier and AD transmitter for recording. Moreover, the efficiency of the prosthesis was measured by pulling its cable forcibly using an AC motor. The excursion and the force on the terminal device were simultaneously recorded.

Methods

Both mechanical and clinical tests were performed.

In the former, the pulling force to open the hook of the prosthesis locked at various elbow angles was measured for evaluation of the effect of the pulley system. The effect of the liner and pulley was also evaluated dynamically by pulling the cable of the prosthesis using an AC motor (Fig. 6).

With a total of 12 amputees i.e. 2 trans-radial (☜2), 9 trans-humeral shoulder disarticulations (✍7, ☜2) and one forequarter (✍1), the effects of the elements of the system were evaluated under various conditions; with or without a liner, with or without a pulley and with or without a harness (Fig. 7).

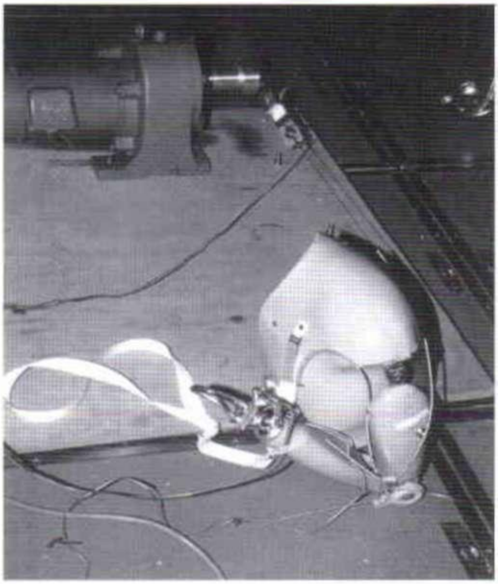

Fig. 6. Dynamic pulling test of a prosthesis.
Pulling force, hook opening force and hook opening angle are measured while pulling a cable using an AC motor.

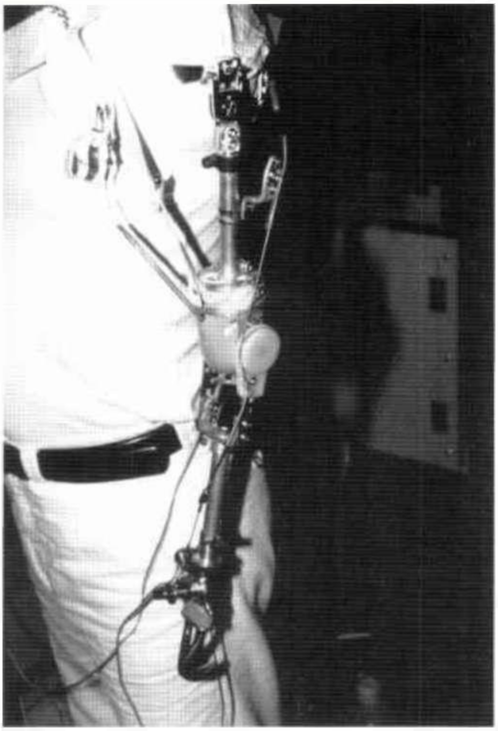

Fig. 7. Dynamic pulling test by a subject.
Pulling force, hook opening force and hook opening angle are measured while the cable is pulled by a subject.

Results

The results are described below separately for the pulley and the liner.

Pulley system

Figure 8 shows the result of the static mechanical test. As compared with a conventional system, the pulley system required less increase in the force for cable movement in relation to elbow flexion, Especially when the

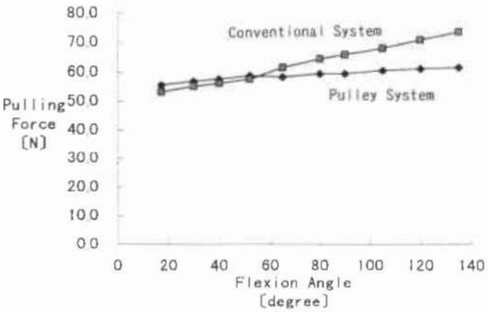

Fig. 8. Results of a static pulling test.
Pulling force is measured when a hook opens 20mm at finger tips.

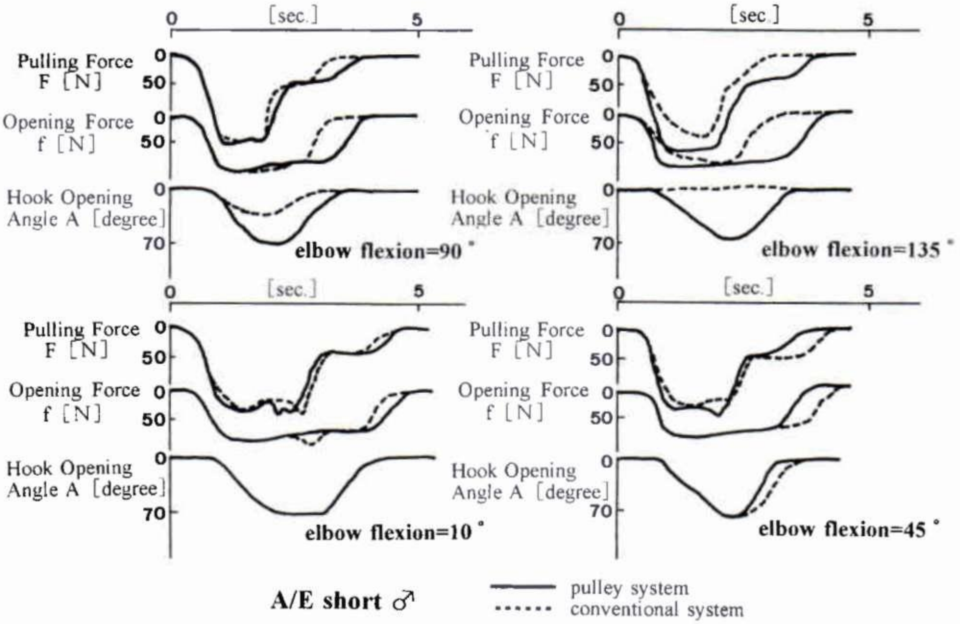

Fig. 9. Result of a dynamic pulling test.
Pulling force, hook opening force and hook opening angle are dynamically measured while a cable is pulled by a subject with a locked elbow joint.

angle of elbow flexion exceeded 60 degrees, the new system proved superior. The pulley system also ensured the maximum opening of the hook because the excursion required for elbow flexion was small. In Figure 9, the amputees' pulling force (F) at each angle of elbow flexion as measured by the test system is shown with transferred opening force (f) and the opening angle (A) of the hook. When the pulley system was used, an almost full opening angle of the hook was obtained for all angles of elbow flexion. For the conventional system the opening angle of the hook was extremely small for elbow flexion angles exceeding 90 degrees. These results show that the pulley system effectively increased the opening angle of the hook. Two examples of hook opening width against elbow flexion are shown in Figure 10. This also shows the system was more effective at increased elbow flexion.

It is clear from the figure that the possibility of opening the hook can be increased by improving the harness. On the other hand, an efficiency assessment performed at the same time showed the use of the pulley resulted in little efficiency increase when the elbow was at the angle of 90 degrees.

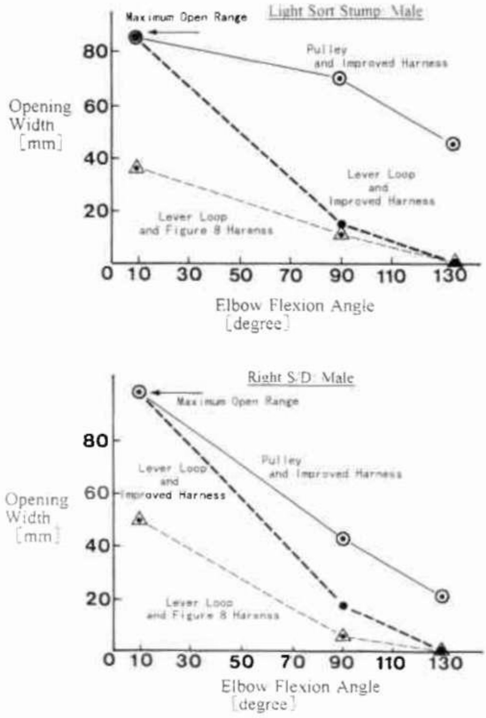

Fig. 10. Result of maximal hook opening width.
Prostheses with or without a pulley, and/or an improved harness are used.

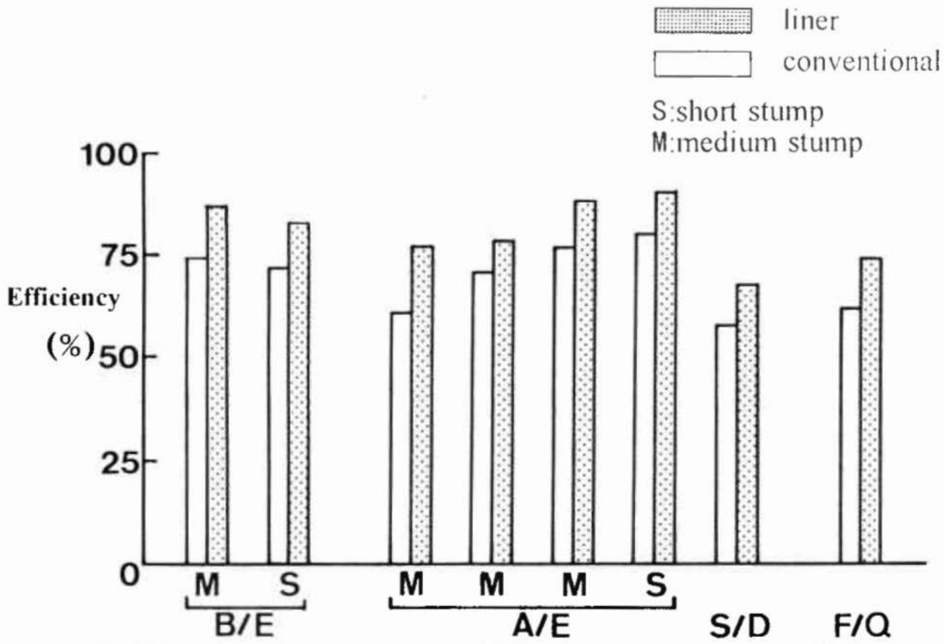

Fig. 11. Comparison of operating efficiency of prostheses with and without plastic liner.

Efficiency is defined as $\frac{\text{hook opening force}}{\text{pulling force}}$ x100%.

Liner housing

The changes caused by the use of the liner housing are shown in Figure 11. All patients using a liner housing on the same prosthesis showed an efficiency increase. In order to assess the effects of pulley and liner under the same conditions, the pulling force and hook opening

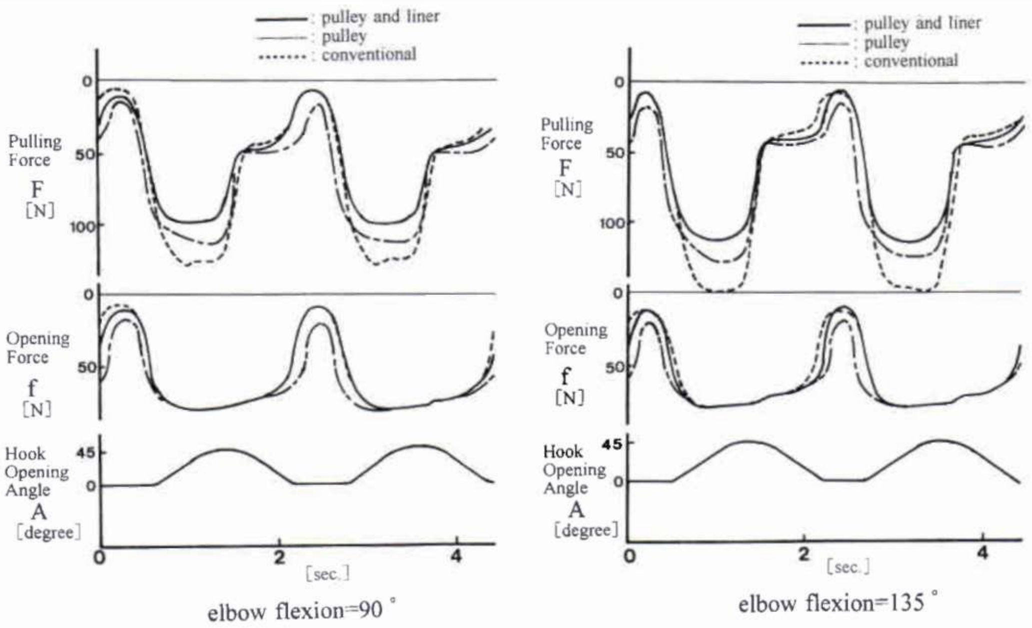

Fig. 12. Result of a pulling test.
Pulling force, hook opening force and hook opening angle are dynamically measured in a test rig.

force were measured on a fixed upper arm prostheses by operating the open-close action with a dynamic test rig using an AC motor. The results are given in Figure 12. This experiment shows the comparison of the pulling force required for the same hook opening in the same prosthesis with and without the housing and also display chronological changes. These results also show the use of pulley and liner (the full line) decreases the force necessary to obtain the same opening force at the terminal device (f), compared with the conventional method (the broken line).

Discussion

It was shown that the pulley system contributed to an improvement in efficiency when the elbow was flexed. A pulley is therefore effective for working conditions at a desk, in which the elbow is consistently kept flexed. In this system, the trunk actions can be used effectively because the cable excursion for elbow flexion is small. In addition, it was confirmed that the use of a low friction liner housing increased the transfer efficiency by 10%. As for the prosthesis operation, it was found through tests using measuring instruments and patients that the combination of this housing, the above pulley system and harness system improved the operation of the body-powered prosthesis. A pulley is effective for a body-powered prosthesis in the situation mentioned above. But in case the elbow is flexed with the hook gripping something heavy, the action cannot last indeterminately. Although a liner housing is effective for transfer efficiency, some force is necessary to keep the hook open because the force is directly transferred. It is important, therefore, to apply these improvements selectively to suitable cases.

Conclusion

Various improvements and developments were made to make a body-powered prosthesis more operable. Their effectiveness was evaluated experimentally. The authors hope to conduct further research so that the newly developed system can be widely used.

Acknowledgement

The authors wish to acknowledge their gratitude to Dr. Dudley S. Childress, director of Rehabilitation Engineering Program and Prosthetics Research Laboratory in Northwestern University, for his helpful comments for this study.

REFERENCES

Atkins DJ, Meier RH (eds) (1989). Comprehensive management of the upper limb amputees. – New York: Springer-Verlag

Carlson LE, Childress DS (1975). The lift lock: a device to increase the lifting ability of dual-control prostheses. *Bull Prosthet Res* **10(23)**, 158-168.