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A case study of reaching by a user of a manually-operated artificial hand

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Abstract

Reaching involves both transport of the hand toward an object and opening of the hand by an appropriate amount before arrival at the object. Movements of a manually-controlled artificial left-hand are compared with movements of the natural right-hand of a proficient user of an artificial hand. Although picking up of objects was slower with the artificial hand, similarities in opening and transport movements were observed in the two hands. Despite major mechanical differences in the systems subserving movement in the artificial and natural hands, the similarities extended to the separate movements of the thumb and finger. The strategy of artificial hand control employed by this subject is discussed and related to training new users of artificial hands.

Introduction

Recently there has been considerable interest in the myoelectric hand including its evaluation in practical, everyday use (Northmore-Ball, et al, 1980). However, the majority of fittings in the U.K. still involve prostheses operated by a control cable attached to a harness on the opposite shoulder. As well as being cheaper and more reliable in use than the present generation of myoelectric hands, users commonly report that the manually-operated artificial hand provides better feedback during use (Sensky, 1980). However, there is little behavioural data on the coordination of movement in artificial hand control. This paper summarizes new findings from a project intended to improve this situation. The basic question asked was whether coordination achieved by a proficient user of an artificial hand is similar to coordination in the natural hand? The answer to this question would be an important first step in the identification of the nature of the skill to be trained in a person newly fitted with an artificial hand.

A major function of the hand is reaching for objects. An important component of coordination in normal reaching is the opening of the hand before the hand reaches the object. Transport may then proceed without pause until the hand encompasses the object. Surprisingly, despite the classic studies of the development of infants' grasp patterns by Halverson (1937), there is little published data on coordination in reaching. However, a series of film studies of reaching movements by adults without disability has recently been carried out by Jeannerod (1981). The main findings were that the degree of hand opening varies for objects of different sizes and the hand begins to close before contact is made with the object, (maximum opening was observed at the same time as the hand began to slow down in its approach to the object). The experiment described below set out to determine whether these findings would apply to a manually-controlled artificial hand.

Subject

A 13-year old girl with congenital absence of her left arm below the elbow was chosen for the study. From the age of two, she had been fitted with a standard below-elbow prosthesis and a juvenile split hook operated by a shoulder harness. One year prior to the study she changed to a functional artificial hand with a good cosmetic appearance (Otto Bock, voluntary opening, catalogue number 8K8). For both types of artificial hand, forward flexion (protraction) of the shoulder girdle is used to tension a cable running from the harness to the hand. This causes the hand to open against the action of a spring that keeps the hand normally closed.

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However, the hook and the Otto Bock hand differ in the way they open. Opening of the hook is single-sided, the "finger" staying in fixed alignment with the forearm while the "thumb" moves to open or close the hand. The Otto Bock hand opens in a double-sided fashion, the thumb and the index with middle fingers moving equal and opposite amounts in opening and closing the hand.

The subject's right hand was her natural hand. Its function was perfectly normal and so the data for the right hand presented below may be treated as control data.

Method

Standing at a waist-high table, the subject was asked on each trial to pick up a 7·5 cm length of wooden dowel placed upright approximately 35 cm from the edge of the table. Two different dowels, of 12 mm and 22 mm diameter, were used alternately on successive trials. With the artificial hand locked in mid-position (as if the radio-ulnar wrist axis were vertical), this task required that the dowel be picked up with the thumb on the side nearer the body opposing the index and middle fingers on the other side of the dowel. When picking up the dowel with the right hand, the subject was instructed to use thumb, index and middle fingers also. Movements were made "at a comfortable speed without knocking the dowel over".

The data reported in this paper are from the third of a series of six consecutive blocks of four trials each. In each block, the first two reaching movements were made with the natural right hand, the second two with the artificial left hand.

Recording of movements was made using a 16 mm Bolex camera with a 35 mm lens mounted 1690 mm above the surface of the table. The camera was run at a nominal speed of 64 frames per second with Kodak Tri-X reversal film. Overhead lighting by two 275 watt photoflood lamps was employed. On every trial the clockwork drive of the camera was rewound and set running before the subject was told to start the reaching movement. The camera was stopped after the object was seen to be grasped and the return movement of the arm had commenced. An electronic counter triggered by the onset of hand movement was included in the field of view of the camera. This showed that trial to trial variations in the running speed of the camera only amounted to some 5% for an average sample period of 15·5 msec.

As an aid to calibration of distance in the evaluation of the film records a sheet of card with a 2 cm lined grid was kept on the surface of the table. To improve the accuracy of digitizing the position and opening of the hand on the film records, three markers were placed on each of the subject's hands (Fig. 1).

Fig 1. Photograph of the subject showing the placement of markers for digitizing position of wrist, thumb and finger on the natural (right) hand and artificial (left) hand.

One was placed on the radial side of the forearm just distal to the wrist. A second was placed over the interphalangeal joint of the thumb and a third was placed on the proximal interphalangeal joint of the index finger. In determining the aperture of the natural hand, a better position for the markers might have been on the tips of the thumb and finger. Unfortunately, it was found that the thumb and finger tips became obscured from camera view by the dowel in the final stages of the movement. However, visual inspection showed that opening of the natural hand was accomplished almost entirely at the metacarpophalangeal joints. (In the artificial hand, this was the case by virtue of its construction.) The movement of the markers may therefore be taken as an accurate representation of aperture. Markers were also placed on the ends of the dowels.

Results

A computer-based system for digitization of film was used to measure the distances between the dowel and the three markers on the hand for each frame of the filmed record of the reaching movements. These distances were then analyzed in various ways as described below. It should be noted that for clarity only a sub-set of the data is presented. These data are from the third of the six blocks of four trials and may be considered typical of the other five blocks.

Reaching with the artificial hand was slower than with the natural hand. Figure 2 shows a plot of the distance of the wrist from the dowel in relation to the time taken for the left and right hands to pick up the wide and narrow dowels. The

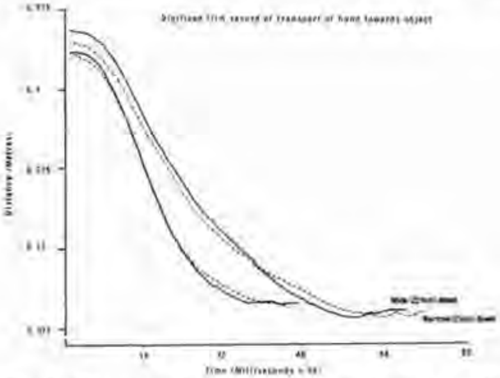

Fig 2. Distance of the wrist marker from the wide (solid lines) and narrow (dashed lines) dowels as a function of time for natural and artificial hands. The two trajectories for the artificial hand are on the right (i.e. they are the slower ones).

digitized data extend 5 frames past the point at which the finger and/or thumb first made contact with the dowel. Both pairs of curves show a similar period of initial acceleration up to about frame 10 followed by a period of roughly constant velocity. However, the artificial hand movements show an earlier deceleration at about frame 16 whereas there is no discernible slowing of the right hand until about frame 22. Contact is made by the artificial hand some 25 frames, or about 50% later than the natural hand.

Data on hand opening for the wide and narrow dowels are given in Figure 3. The distance between the interphalangeal joints of thumb and finger is plotted as a function of time normalized by the time to contact. The fourth division on the horizontal axis (relative time 100) is the time of contact. The first three divisions on the

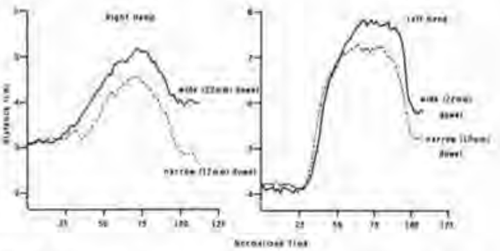

Fig 3. Distance between finger and thumb for the wide (solid lines) and narrow (dashed lines) dowels as a percentage of the time to contact for natural (left panel) and artificial (right panel) hands.

horizontal axis thus represent 25%, 50%, and 75% of time to contact. It will be observed that the vertical axes for left and right hand cover slightly different ranges, although they are to the same scale. This reflects differences in the physical dimensions of the natural and artificial hands. It should also be noted that the subject started the artificial hand movements with the tension off the shoulder harness cable so that the thumb and finger tips were touching. In contrast, movements with the natural hand were started with the hand relaxed giving a thumb-finger tip gap of about 15 mm. Thus the change in hand opening from the start and end of each record is different for the left and right hands.

The figure clearly shows two major points of similarity in the opening of the two hands. Firstly, opening of the hand achieves a maximum in the course of transport which exceeds the final degree of opening required to grasp the dowel. In both hands the difference between the maxima for wide and narrow dowels is of the same order as the difference in dowel diameters. Secondly, from about 25% up to about 75% of the time to contact, both hands show a steady opening. But there is a striking difference in the last 25% of the time course. Whereas the right hand closes at approximately the same rate as it opened, closing of the left hand is apparently delayed—the hand opening shows a plateau rather than a peak—and in consequence the rate of closing of the artificial hand is considerably faster than its rate of opening.

The picture presented so far is thus one in which differences between the hands appear in the later parts of the movement as the object is approached. The psychological literature on motor skills often distinguishes between two types of control; (a) movement made without reference to its relation to the environment (open-loop), (b) movement that is corrected as it progresses on the basis of feedback about its relation to the environment (feedback-regulated). In skilled performance it is usually found that the early part of a movement is launched in open-loop fashion (often ballistically with the agonist muscles providing a large, impulsive force at the very beginning of the movement). Corrections on the basis of feedback are only made in the later stages depending on how well the target for the movement is approached, (Keele, 1968; Beggs and Howarth, 1972). We may therefore suppose that the start of the transport movement in reaching is open-loop. Moreover, the similarity of the early of the part of the trajectories for the left and right hands suggests the underlying commands to the muscles (motor programme) in the two cases are equivalent.

What could underly the differences between the reaching movements of the two hands in the later stages of the movements, when feedback regulation of the movement might be expected to be important? Our analysis of the data so far shows the approach velocity of the artificial hand is slower and it is held open for relatively longer. We now present a further analysis aimed at a better appreciation of the problems involved in artificial relative to normal hand control in the later, approach stages.

In Figure 4, as a function of time relative to contact, we have plotted the perpendicular distance of the thumb and the index finger from an imaginary axis joining the wrist and the centre of the dowel. Positions to body left of this axis are represented as positive. Thus, for example, with the axis aligned straight forward with respect to the body the right hand thumb is given as positive and the right hand index finger distance is given as negative. For the left hand in a similar position the positive and negative signs are, of course, reversed.

Consider first the left panel of Figure 4 which shows the data for the natural right hand. For about the first third of the time to contact there is parallel movement of thumb and finger relative to the wrist-dowel axis. This is because the hand starts by swinging round as it is transported toward the dowel until the gap between the thumb and finger tips spans the wrist-dowel axis.

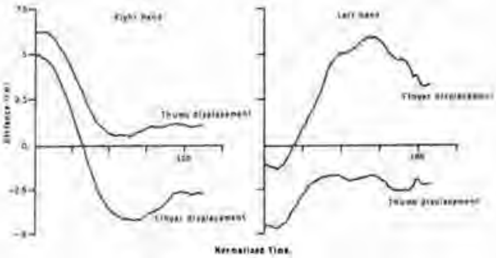

Fig 4. Distance of the finger and thumb from an axis joining the wrist marker to the wide dowel for natural (left panel) and artificial (right panel) hands. In both panels, the curve for the finger is the one nearer the horizontal axis at time zero.

The more interesting aspect of the data is they show that, while the thumb holds a more or less fixed position relative to the axis, the index finger is largely responsible for the opening and closing of the hand. This possibly reflects differences in the ease of controlling fine movements at the metacarpophalangeal joints of the finger and the thumb. But it may also be seen to confer a simpler visual relationship between the object and the approaching hand assuming attention is focussed on the relation between thumb and dowel. This presumably simplifies processing of visual feedback so making any adjustments to the approach movement easier and quicker.

Turning to the right panel in Figure 4 the data on the artificial hand show an almost identical pattern of movement of the thumb and finger relative to the wrist-dowel axis. Moreover, the similarity of the artificial and natural hands is also seen in Figure 5 when reaching for the narrow dowel. This correspondence is all the more remarkable when one considers the nature of finger and thumb movement in the artificial hand. The mechanical system is such that tensioning the cable against the spring holding the hand closed leads to simultaneous movement of the thumb and finger in opposite directions. The amount of movement is equal for thumb and finger. Given the mechanical functioning of the

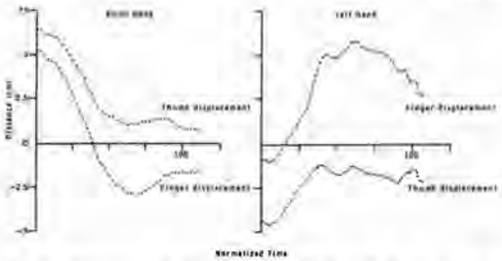

Fig 5. Distance of the finger and thumb from an axis joining the wrist marker to the narrow for natural (left panel) and artificial (right panel) hands. In both cases, the curve for the finger is the one nearer the horizontal axis at time zero.

hand, it is thus very surprising that the subject is able to operate her artificial hand during reaching in such a way that the use of thumb and finger appears normal.

Further examination of the film showed that the subject achieved the invariance between the thumb and wrist-dowel axis in at least two ways. On some trials the direction of movement of the artificial hand was reversed before the object was contacted. The speed reversal matched the speed with which the thumb would otherwise have approached the dowel. Such reverse transportation can be seen in both curves for the artificial hand in Figure 2. It is not present in the natural hand transport curves. Rotation of the arm about the wrist was also observed on some trials as a result of abduction of the arm at the left shoulder joint combined with internal rotation. This manouevre maintained a relatively fixed distance of the thumb from the axis as the hand closed, without any overall transportation movement observed at the wrist.

Conclusions

Analysis of the film records of reaching indicates that the proficient user of an artificial hand uses the thumb as the basis for aligning the grasp as the hand approaches the object. This parallels natural hand usage and it is reasonable to suppose that it simplifies processing of visual feedback about the relation of the hand to the object. This feedback is needed in making adjustments to the approach trajectory of the hand. However, this strategy (which did not appear to be conscious on the part of the subject) required manoeuvres of the artificial hand that presumably interact with the problems of control due to the shoulder-based movements. In future research in this area there would seem to be a strong argument for taking the methodological approach of Soede (1980) who has developed objective indices for the ease of control of different types of artificial hands.

For example, we observed a number of similarities between normal hand function and the functioning of the artificial hand, but the movements of the artificial hand were much slower. An important question in contemplating possible changes in artificial hand design, is to what extent the slowness is due to the need to employ muscles, normally used in gross movement, for fine movements. Or, does the slowness result from an added dependence on vision due to lack of sensory feedback from the extremity? With reference to the last possibility, a quick test showed that the subject was only able to grasp the dowel with eyes shut one out of five times when she was asked to pick it up from a known position using her artificial hand. Using the natural hand, with her eyes shut, she picked up the dowel five out of five times. But, whether the slowness arises from the employment of gross muscles, from an added dependence on visual feedback or a combination of both factors, the real issue is how much more difficult is it to use the artificial hand? Techniques, such as those suggested by Soede (1980), should be most useful in assessing the attention demands of various manouevres of an artificial hand.

The present study has treated the performance of a single user of an artificial hand. The subject was a "good" user in that she wore her prosthesis regularly and was proficient in its operation in activities of daily living. It would be interesting to know whether other users would exhibit similar patterns of control. In particular, what is the nature of movements used by people who are less proficient, who have only recently been fitted with an artificial hand? And how do consistent patterns of movement, such as those seen in this study, develop?

The answers to these questions are obviously central to evolving an efficient training programme for new wearers of artificial limbs. But even at this stage certain implications for the goals of training by therapists may be drawn. We will consider these in order of their occurrence in the reaching movement, although this may not be the most appropriate learning sequence. So that the first part of the transport movement can be open-loop, the learner should have a clear spatial target in mind before starting to move the hand. Training at this stage might be based on a game where the hand is used (without opening) to knock over a target placed at various positions. After several trials, the learner could be encouraged to close his or her eyes just before starting the movement.

The second component, hand opening, might be introduced as a static task, with the hand immediately in front of the object. The goal would be to open the hand just wider than the perceived object size and hold it at that width. In this exercise it would probably be useful to have a set of standard objects with clear size gradations. Again, in later trials, the learner could be encouraged to close the eyes just before starting to open the hand. This would emphasize the need to relate the degree of hand opening to a clear mental image of the object.

The two components, transport and hand opening, might be most easily put together into a reaching action by having the learner initiate both elements together. Then, as skill develops, opening of the hand may be allowed to occur later, subject to the constraint that a maximum aperture exceeding the object size be attained by about three-quarters of the way through the action. The learner should be directed to focus attention on the thumb relative to the object from about halfway through movement. To discourage the learner from monitoring the hand too early in the movement, it would probably be best to start the movement looking at the object. A helpful exercise might be to ask the learner to keep the hand open at the maximum and simply bring the hand up to the object, stopping with the thumb just touching the object.

Finally, strategies to cope with simultaneous closure of thumb and finger would have to be outlined. There might be a problem explaining these to younger children, although static practice with the hand opened and closed to keep the thumb in fixed alignment with a simple target might help.

Throughout training, and particularly on trials performed with the eyes shut, video feedback showing performance of the artificial hand could be very useful to the learner as well as the therapist. Moreover, the use of video records to show the learner his or her improvement in performance over a number of sessions would provide strong positive reinforcement. If video were used to demonstrate similarities between artificial and natural hands, acceptance of the prosthesis might be improved by emphasizing the similarities between artificial and natural hand function. This might become a criterion for the wearer accepting the hand as "a part of him-or herself".

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