A Myoelectric Control Evaluation and Trainer System

Anne-Caroline Dupont and Evelyn L. Morin

Abstract—**A computer program, which was developed to train and assess child upper limb amputees in the use of myoelectric control, is described. The program permits a user to open and close a graphic hand using myoelectric control and automatically saves assessment results. The program was designed to be entertaining for children and easy to use for therapists.**

Preliminary testing of the program was done with fifteen nonamputee adult volunteers. The results indicate that the program is a useful tool for myoelectric training and assessment. All subjects improved at myoelectric control, the improvement being greater at the beginning of a ten day training period than at the end of it. The use of the dominant versus nondominant arm for control did not have any effect, and the error most commonly produced was undershooting.

I. Introduction

PROSTHESES that employ myoelectric control systems are now well accepted by upper limb amputees [1]. Although the causes of upper limb deficiency are varied, they will not likely be eliminated within the next few years. Therefore, the percentage of amputees in the population will remain constant and since the population of Canada is growing, the need for prosthetic devices will increase. The incidence of congenital limb malformation is approximately 1 in 2760 live births in Canada, excluding medical disasters like the thalidomide episode. The incidence of babies born with upper-limb congenital deficiencies for which myoelectric fitting seems appropriate is 1 in 9400 [2]. In 1989, there were 392,661 live births in Canada [3], which gives approximately 42 new patients needing myoelectric prostheses. This approximation does not take into account acquired amputations. Acquired deficiencies account for 15% of upper-limb deformities [2] and assuming that 44% of acquired upper limb amputees are good candidates for myoelectric prostheses (using the same ratio as for congenital amputees), there are approximately 7 new patients with acquired upper-limb deficiency who are good candidates for myoelectric prostheses, giving a total of approximately 49 new upper-limb amputees who need myoelectric prostheses every year in Canada.

It is now accepted that a two-year old child with a congenital arm deficiency who has normal intellectual and social development is ready and has the maturity to learn to control a nonpassive prosthesis [4]. Sörbye showed, between 1977 and 1980, that children fitted with myoelectric prostheses are better users if they are fitted at a young age [5], [6]. He recommended that children be fitted between the ages of $2\frac{1}{2}$ and 4 years. Early fitting has the advantage that the child will accept the prosthesis as a part of his/her body image more easily and that myoelectric training will prevent muscle atrophy in the residual limb [5], [7]. Caldwell has studied young children fitted with myoelectric prostheses and has concluded that preschool children use myoelectric prostheses spontaneously and naturally [8].

Training is one of the most important factors in acceptance of a myoelectric prosthesis [7], [9], [10]. Stein and Walley [11] named the lack of occupational therapy as one of three reasons why some amputees do not wear their prostheses, the others being a painful stump and the feeling that the prosthesis is not needed. In a study of amputee rehabilitation, Herberts *et al.* [12] found that the acceptance rate of myoelectric prostheses doubled if patients were trained to use their prostheses properly. Since children are now fitted as young as 3 years old with myoelectric prostheses [5], [7], [8], [13], [14] it is important to find effective methods to train young children.

The most complete program for upper-limb amputees learning to use a myoelectric prosthesis comprises three types of training: myoelectric signal training, control training and functional training. Not all prosthetic centres and clinics offer all three types of training to their patients. Myoelectric signal training is the most basic level of training. For two-site two-state control, the user learns to contract two muscles in the residual limb independently and to relax those same muscles on demand [15]–[18]. For a 1-site 3-state control system, the user learns to produce a weak and a strong contraction of the chosen control muscle. Typically, this phase of the training takes about 3 to 4 hours [15], [17]. Control training involves learning to use the controlling muscles appropriately. Feedback is provided using modified toys, computer games or an actual prosthesis [15], [16], [19]. Functional training is introduced by the therapist in the form of a series of activities to be performed daily by the amputee at home using his/her prosthesis. These include toiletting, hobbies and appropriate two-handed activities [15]. Training accomplishes three important tasks: becoming accustomed to wearing the prosthesis, becoming efficient with the prosthesis and learning to view the prosthesis as a part of the body image.

Manuscript received July 28, 1993; revised May 20, 1994. This work was supported by NSERC Operating Grant #0042545.

The authors are with the Department of Electrical and Computer Engineering, Queen's University, Kingston, Ontario, Canada.

Department of Electrical and Computer Engineering, Walter Light Hall, Queen's University, Kingston, ON, K7L 3N6 Canada.

IEEE Log Number 9403813.

1063–6528/94$04.00 © 1994 IEEE

It is also important to assess the ability of an amputee to use his/her prosthesis. Each prosthetic and rehabilitation centre uses a different assessment scale and sometimes different methods to evaluate myoelectric control [12], [13], [15], [20], [21]. These methods are often subjective and therefore assessment results from one centre to another cannot be compared. A precise and quantitative evaluation program would permit a therapist to identify specific control problems with the amputee and/or the prosthesis. Also, using a training and evaluation program before fitting an amputee with an arm prosthesis would help determine if a myoelectric prosthesis is suitable and which kind of control system would best accommodate the patient. Two objective computer-based assessment systems for myoelectric control have been reported. Lovely, Stocker, and Scott [15] have incorporated a performance database into a computer game myoelectric trainer. While the child is playing the game, the computer keeps track of specific information such as the time to complete the task, erroneous movements, target overshoot and total time of playing. A computerized assessment tool has been developed at the Hugh MacMillan Rehabilitation Centre (HMRC) [21] but it is not used as a training program, as it does not have sufficient graphics quality nor does it provide rewards for successful actions.

Computer graphics simulations have been used for training and evaluating patients in control of upper limb functional electric stimulation (FES) systems. Durfee *et al.* [22] developed a simulator to evaluate shoulder motion as a command source for FES grasp restoration systems. The simulator consisted of an animated grasping task in which a hand, displayed on a video screen, was opened and closed under control of the command channel. The grasping task consisted of closing the animated hand around a circular object and moving the object from one table to another. Performance was rated by the amount of time required to complete a set number of transfers and by the number of times the object was dropped (too little grasp force) or crushed (too much grasp force). Smith *et al.* [23] reported on development of a computer simulation for training prospective users in operating a shoulder motion transducer for neuroprosthetic hand control. A user opens and closes an animated hand to determine if the transducer parameters should be modified for better control.

This paper describes a computer-based system, which was developed to train young upper limb amputees in the control of myoelectric hand prostheses and simultaneously assess their performance. The computer program was designed to be attractive for child users and to be easy to use for therapists. The program provides a record of the quantitative assessment of the user's performance.

II. Methods

A. Program Description

To fulfil the need for concurrent training and assessment of amputees in the use of myoelectric control systems, a computer program called MCETS (Myoelectric Control Evaluation and Trainer System) which combines an interactive graphics presentation with a performance assessment component was created. MCETS was written in Microsoft C for compatibility with an electrode placement program, MSAS (Myoelectric Signal Assessment System), developed at the Hugh MacMillan Rehabilitation Centre (HMRC) in Toronto. The program was written in four modules and comprises five executable files: the main program MCETS and the four option programs DEMO, NEW, RETEST and RESULT. A program flow chart is shown in Fig. 1. Each option program can run independently. DEMO provides a demonstration to familiarize users with the training and assessment program; a training sequence is presented but the animation is controlled by keyboard cursors instead of the myoelectric signal. Both NEW and RETEST are full training and assessment programs. They include a full training session and the means to view the trial per trial and cumulative results. NEW is used for a patient being tested for the first time and asks the therapist to enter the patient information and creates a new database file for saving the assessment results. RETEST assumes that the patient has been tested before and opens an already existing database file to which the new results are appended. All patient files have the extension INF for easy recognition. RESULT allows viewing of a patient's file, including the patient information and all of the cumulative assessment data, test by test.

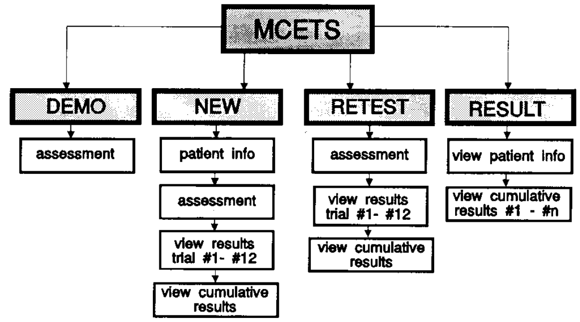


Fig. 1. Program flow chart.

The first training session (using NEW) proceeds as follows. An introduction screen is presented, which explains the upcoming steps of the program. The therapist is then asked to enter the patient information—last and first name, birth date, sex, type of amputation (congenital or acquired), date of amputation (if acquired), cause of amputation (if known), side of amputation (left, right or bilateral), level of amputation and previous prosthesis worn. This is saved in a database file. The therapist is asked to select whether the right hand or the left hand is to be animated and to select one of three difficulty levels: easy, medium or difficult. The training session for the user starts at this point. An illustration of the task presentation screen is shown in Fig. 2. A target hand (colored green) is presented as a mirror image of the animated hand (colored brown). The user is asked to open or close the animated hand using myoelectric control, until it matches the target hand and to stop the animated hand in that position. A purple star appears at the finger tips and a "beep" is heard whenever the animated hand is in an acceptable position. After the hand has

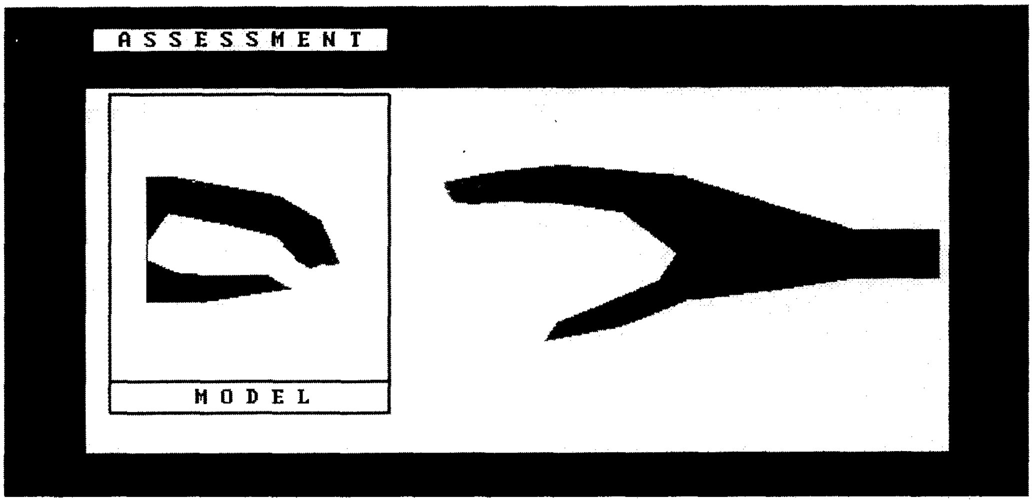


Fig. 2. Task presentation screen.

TABLE I
TRAINING SESSION TASKS

Task #	Task description
1	from position #5, close to position #1
2	from position #1, open to position #4
3	from position #4, open to position #8
4	from position #8, close to position #3
5	from position #3, open to position #10
6	from position #10, close to position #7
7	from position #7, close to position #2
8	from position #2, open to position #5
9	from position #5, close to position #0
10	from position #0, open to position #9
11	from position #9, close to position #6
12	from position #6, close to position #3

remained in the target position for 1 second, a congratulations message appears and a musical phrase is played as a reward. Following a success a new target position is displayed.

Through experimentation with the graphics functions offered by Microsoft C5.1, the erase-and-draw method for animation was selected as it gave the best results for creating motion of the hand. On the animated hand, the wrist and hand are fixed. A rectangle is defined around the fingers and thumb. To simulate motion, the rectangle is erased and re-drawn with the next finger-thumb position (more opened or more closed, depending on the function selected). Eleven finger-thumb positions were defined and numbered 0 (most closed) to 10 (most opened). For reasonable animation speed, all finger-thumb position images are stored in memory before the animation begins. A training session comprises twelve different opening and closing tasks, which are listed in Table I. The target positions are presented in random order and the user is required to stop in each of the eleven defined positions at least once; the tasks do not represent all the existing possibilities. Each test comprises the same twelve tasks, so that a comparative evaluation of the assessment parameters can be made across tests.

It was decided to control the animation of the graphic hand using interrupts and to use the serial port (RS-232) for the input of the myoelectric control signal so that no modification to the computer would be necessary to run the program and because the serial port permits a 2-bit parallel input from an external device. The user's performance is assessed continuously during the training session by recording all interrupts, along with the time at which they occur and the hand position at that time. It is possible that a user can produce more interrupts during one trial than the computer can handle; a message indicating a data overflow will appear on the assessment data. This data should not be saved since the computer was not able to record all the pertinent information. If this happens repeatedly with a user, a need for more signal training is indicated. Once all trials of the training session are completed, the computer analyzes the data recorded and displays an assessment of each trial. The assessment data from all twelve trials are combined to produce the cumulative assessment record, which includes the number of correct openings, number of correct closings, number of incorrect openings, number of incorrect closings, number of undershots while opening, number of undershots while closing, number of overshots while opening, number of overshots while closing, total cocontraction time (in seconds), total control time for the test (in seconds) and average control time per trial (in seconds). A correct opening or closing occurs when the user selects the proper function for the task presented. An incorrect opening or closing occurs when the user selects the improper function for the task presented. An undershot occurs when the user stops the animated hand before reaching the target position. An overshot occurs when the user does not stop the animated hand until beyond the target position. Co-contraction occurs in a two-site two-state system when the user contracts both muscles, thus selecting both functions; neither function is activated. Control time is the time used to control the hand display and does not include the time taken by the computer to draw the hand on the screen. This parameter reflects all other parameters since any type of error results in an increase in control time. The cumulative assessment data are saved in the patient's file which can be viewed later.

To assure a uniform environment during training and during use of the prosthesis, the forearm of the prosthesis (socket and processor) is to be used with the training and assessment program; the output of the control unit of the myoelectric prosthesis is used to provide the input to the computer. When evaluating a child in a clinical setting before he/she is fitted with a myoelectric prosthesis, a test socket and control unit should be used. In this way, the physical environment of the residual limb is maintained and the myoelectric signal processing remains the same. Commercially available prostheses do not all enclose the control unit in the same location within the prosthesis; the control unit can be placed in the forearm or the hand of the prosthesis. Therefore, each brand and model of prosthesis requires a different electronic interface. For a number of prostheses, the only electronic circuit needed will be an isolation amplifier/driver with a gain which will bring the prosthesis battery voltage level to a TTL voltage level. For other prostheses a part of the processor will have to be included in the electronic interface circuit.

To obtain a high degree of correlation between the user's ability to control the hand image and to control his/her myoelectric prosthesis, the graphics hand should be controlled in the same way as the prosthetic hand. The time delay between a function request (via myoelectric signal production) and initiation of the function must be reasonable (within 300 ms). This is achieved through using the output of the myoelectric control unit to request the interrupts which control the graphics animation. As well, timing of the hand's operation should be similar to that of a prosthetic hand. Myoelectric hands for children take between 0.8 sec and 2.0 sec to go from a fully closed position to a fully opened position [24]–[26], and vice versa. The time taken to open/close the hand completely is dependent upon the processing speed of the computer. Measured values varied between 0.95 sec (25 MHz 80386 IBM compatible computer) and 1.91 sec (12 MHz 80286 IBM compatible computer). For computers operating at faster speeds, it may be necessary to add delays in the drawing routine to maintain proper opening and closing speeds.

Since the relationship between controlling the hand image on the computer screen and controlling a myoelectric prosthesis must be obvious, the graphic hand looks realistic and is offered in a left or right side model to match the amputation side. Since this program is aimed primarily at children, the program's graphics are designed to be attractive in order to maintain a child's interest during the entire training and assessment period. The tasks are easy to understand so that the results of the assessment will not be skewed by confusion about the required task and success is clearly indicated so that the control test is not a perception test.

There are three difficulty levels in the training and assessment program. The difficulty levels do not involve the actual control of the hand, but rather the precision with which the target positions must be reached. When training with a difficulty level of *difficult*, the target position must be matched exactly; while training with the *medium* level, a range of one position on either side of the target is acceptable for a success; and while training with the *easy* level, a range of two positions on either side of the target is acceptable. The provision of difficulty levels makes the program a useful training tool for both beginners and more advanced users in myoelectric control.

B. Program Testing

Once functioning, the system was tested to pinpoint any technical difficulties and to determine its effectiveness as a training tool through charting the assessment parameters. Fifteen normally limbed adult subjects, twelve men and three women, volunteered to train with the program. The subjects were aged from 23 to 45 years old, with a mean of 27.2 years and a standard deviation of 6.2 years. None had any previous myoelectric control experience. They were trained every week day for two weeks, for a total of 10 days. Each training session involved completing one training regimen, at each of the easy, medium and difficult levels. The muscles trained were the wrist flexor and the wrist extensor muscles which are most commonly used for two-site two-state myoelectric control by below-elbow amputees. Since only one arm was to be trained, it was decided to train using the dominant arm for seven subjects and the nondominant arm for the other eight subjects to avoid any skew in the data resulting from one or the other arm being easier to control. Five aspects of the training were studied: the effect of the three difficulty levels, the training effects of the program, the learning pattern of the subjects, the control strategies used by the subjects and the effect of using the dominant or nondominant arm for myoelectric control.

At the first training session, myoelectric signal recording sites were identified at the proximal ends of the wrist flexor and wrist extensor muscles. These sites were marked on the skin with permanent ink to ensure that the same muscle sites were used on each subsequent day. The skin at the recording sites was cleaned with rubbing alcohol and conducting gel was rubbed into the skin to reduce the skin impedance. Surface Ag–AgCl electrodes were then fixed in bipolar configuration at the muscle sites. Initially, NEW was used to record the subject's information and to train and assess the subject at the easy level. Subsequently, RETEST was used to train and assess at the medium and at the difficult level. Thus, each subject was trained and assessed at all three difficulty levels.

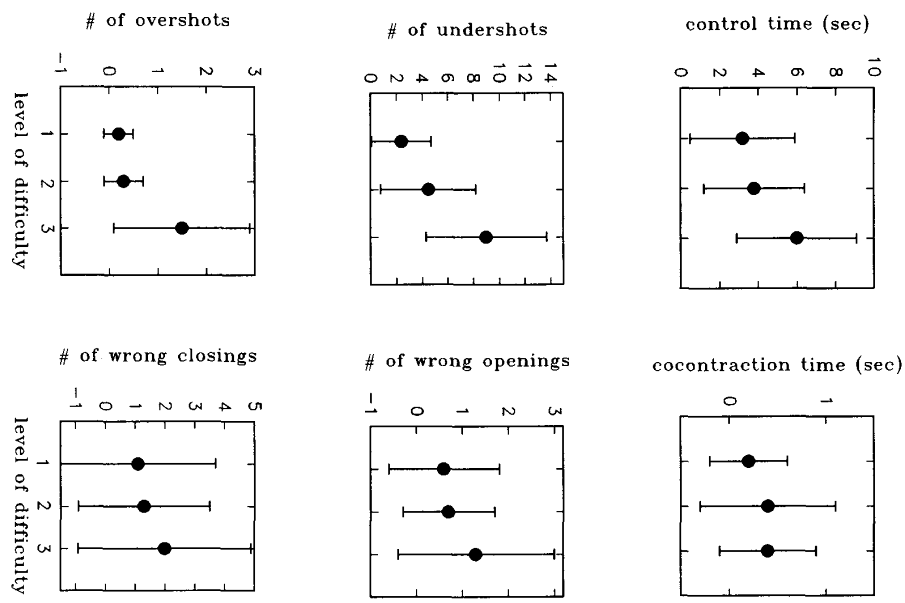


Fig. 3. Control time and error incidence versus difficulty level. Level 1 = easy, Level 2 = medium, Level 3 = difficult. Top to bottom, left: control time, undershots, overshots. Right: cocontraction time, wrong opening commands, wrong closing commands. Error bars represent ±1 standard deviation.

The data from all assessments were saved in one file for each subject. At subsequent training sessions, RETEST was used three times, once for each level of difficulty.

For each subject, the control time, number of undershots, number of overshots, cocontraction time, number of wrong openings and number of wrong closings were summarized for each difficulty level. Since the total control time taken for each training session is an overall parameter which reflects all other parameters, the control time alone was used in some of the statistical analyses. Mean control times to complete a training session at the easy, medium and difficult levels were calculated by averaging the total control times from all subjects over all 10 experimental days (150 data points averaged per difficulty level). These mean control times were compared using paired Student t-tests to determine if the different difficulty levels offered a significantly different degree of challenge. A Student t-test was performed on each parameter averaged across all subjects on the first experimental day versus the tenth experimental day, to assess for significant improvement in myoelectric control performance. The learning pattern was estimated by performing a curve fit on the plotted mean control times for each difficulty level.

TABLE II
IMPROVEMENT OF ERROR BETWEEN DAY 1 AND DAY 10 (df = DEGREE OF FREEDOM)

measured parameter	level of difficulty	one-tailed paired t-test	df	Significance
undershots	easy	t = 4.36	14	P < 0.0005
	med.	t = 4.88	14	P < 0.0005
	diff.	t = 3.47	14	P < 0.005
wrong opening	easy	t = 2.38	14	P < 0.025
wrong closing	med.	t = 2.54	14	P < 0.025
control time	easy	t = 3.98	14	P < 0.001
	med.	t = 3.31	14	P < 0.005
	diff.	t = 4.04	14	P < 0.001

III. RESULTS

The mean control time to complete a training session increased with the difficulty level, as shown in Fig. 3. The mean control time to complete a training session at the easy level was significantly different than the mean control time to complete a training session at the medium level ($P = 0.0105$). A similar result was obtained when comparing the medium and the difficult level ($P \approx 0$). The number of undershots and overshots displayed an increase with difficulty level. The number of wrong openings, number of wrong closings and cocontraction time showed an increase, although not as pronounced as the number of undershots and overshots. These results indicate that the difficulty levels offered three degrees of challenge for the subjects.

For each difficulty level, all subjects improved their performance over time although the learning pattern varied considerably among subjects. The number of undershots at all difficulty levels and the number of wrong opening commands at the easy level and of wrong closing commands at the medium level significantly decreased over the ten day training program while the incidence of other errors did not decrease significantly. There is a significant decrease in control time at all difficulty levels, indicating that training resulted in improved myoelectric control performance. These results are summarized in Table II.

TABLE III
CURVE FITTING PARAMETERS (df = DEGREES OF FREEDOM)

difficulty level	A	error on A	B	error on B	C	df	chi square	signifi-cance	good fit?
easy	5×10^8	4%	11.4	7%	0	7	3.458	$P > 0.80$	yes
medium	5×10^8	4%	9.7	7%	0	7	1.462	$P > 0.98$	yes
difficult	5×10^8	5%	8.2	9%	1	7	1.954	$P > 0.95$	yes

The mean control times were plotted versus the day of the training, for each difficulty level as shown in Fig. 4; the error bars are ± 1 standard deviation of the mean control time. It can been seen that the curves are nonlinear, the decrease in control time being sharper at the beginning of the 10 day period. A fit of these curves was done using the curve-fitting option in Sigma Plot version 5.0. The following general form for all three curves was obtained:

$$y = A^{\frac{1}{x+B}} + C$$

where y is the control time in seconds, x is the day number and C is the (asymptote $-$ 1) where the asymptote is the minimum control time which was estimated to be 1.0 second for the easy and medium level and 2.0 seconds for the difficult level. The values for A and B were calculated using a weighted fit and are shown in Table III, along with the errors on the parameters and the chi square test for normal residuals.

When using the program, all subjects produced more undershots than overshots. Comments from the subjects indicated that an overshot was perceived as a more serious error than an undershot and that they used undershooting as a means of avoiding overshooting. The incidence of undershots was between 7 to 54 times the incidence of overshots. No significant differences were found in the control times between the subjects who used their dominant arm for control and the subjects who used their nondominant arm.

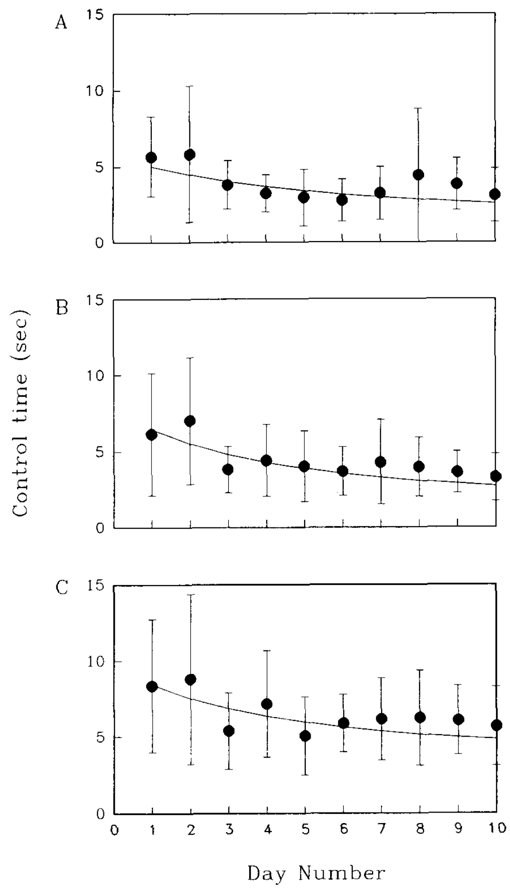


Fig. 4. Learning curves. (A) Easy level (data points ± 1 standard deviation). Equation for curve fit is: $y = (5 \times 10^8)^{\frac{1}{X+11.4}}$. (B) Medium level. Equation for curve fit is: $y = (5 \times 10^8)^{\frac{1}{X+9.7}}$. (C) Difficult level. Equation for curve fit is: $y = (5 \times 10^8)^{\frac{1}{X+8.2}} + 1.0$.

IV. DISCUSSION AND CONCLUSION

MCETS is an updated and expanded version of an earlier computer based assessment program—the Myoelectric Control Assessment Program (MCAP)—developed several years ago at the Hugh MacMillan Rehabilitation Centre (HMRC). Due to poor graphics quality, MCAP was not used for myoelectric control training. MCETS was developed to provide a control training environment in which a user's control ability is quantitatively assessed concurrently with training. MCETS was designed to be used primarily with child amputees. Thus, care was taken to make the program appealing to children through attractive graphics and the provision of visual and auditory rewards for successful completion of the myoelectric control tasks. As well, the program was designed to be used in short tests of 12 tasks each-each test generates a complete assessment record. Depending on the capability of the user, each test would last a few minutes and as many tests as desired could be included in a training and assessment session. Thus to avoid user boredom, several short sessions of training with MCETS could be scheduled throughout the client's myoelectric control training program.

The assessment system was designed to be objective in its evaluation and to help determine specific control problems with each individual tested. It is repeatable to allow for charting improvement over time and for comparative myoelectric control studies of the amputee clientele. The quantitative assessment parameters provide a picture of how accurately the myoelectric control system has been adjusted to the individual user, which will affect how well the user functions within the myoelectric control channel. Inefficient control strategies adapted by long-term users to overcome deficits in myoelectric control systems, which have not been properly optimized, may also be detected. The number of correct openings/closings versus the number of incorrect openings/closings, indicates whether the user can reliably access a desired prosthesis function from the rest state. The number of overshots indicates whether the user can reliably stop the prosthesis at the desired position; a high number of overshots may mean that the hand functions are accessed too easily and the switching levels should be raised. The number of undershots indicates whether the user can move smoothly from an initial to a desired position without hesitation; a user may employ undershooting as a means of avoiding overshooting if the switching levels have been set too low. A high co-contraction time is evidence that a user has difficulty activating the muscle control sites independently and more signal training is necessary. As myoelectric control systems become more sophisticated, allowing users to reliably access more than three states, quantitative assessment of a user's performance will become more important for optimization of the controller.

Initial testing of the program was done using adult volunteers. The first objective was to discover and correct any technical difficulties with the program. The only difficulty encountered was an interrupt overflow (more interrupts were requested than could be handled), which occurred because of the subject's inability to maintain a steady contraction level. In a clinical setting, this would indicate a need for more signal training. The second objective was to test the program with subjects who would most easily understand the goals of the program and what was required during testing. If adult volunteers had been unable to perform adequately with MCETS, then it would not have been suitable for use with children. Results showed that the number of errors and the control time increased with difficulty level, demonstrating that the difficulty levels offer different degrees of challenge. The subjects' control time decreased over the ten-day training period in an asymptotic manner, demonstrating that the program is effective for myoelectric control training with the greatest training effect occurring during the first few training sessions. The use of the dominant or non dominant arm for training did not result in any difference in control ability, which has been noted previously [3, 27]. The results of the testing confirmed that the program had met the goals of the development: to provide a computer-based training and assessment environment for on–off myoelectric control.

MCETS has been sent to the Wascana Rehabilitation Centre in Regina, Sask. where the program will be used to train and evaluate patient amputees and to do a myoelectric control study among its amputee population. A copy of the software was also sent to HMRC in Toronto where it will replace MCAP.

ACKNOWLEDGMENT

The authors wish to thank the staff at the Hugh MacMillan Rehabilitation Centre in Toronto for providing pertinent information about their Myoelectric Control Assessment Program (MCAP). Thanks is also extended to occupational therapists of the Hôpital Marie-Enfant in Montreal, the Institut de Réadaptation de Montréal and the Wascana Rehabilitation Centre in Regina for their input.

REFERENCES

[1] R. N. Scott and P. A. Parker, "Myoelectric prostheses: State of the art," *J. Med. Eng. Technol.*, vol. 12, pp. 143–151, 1988.

[2] P. M. McDonnell, R. N. Scott, and L. A. McKay, "Incidence of congenital upper-limb deficiencies," *J. Assoc. Children's Prosthet. Orthot. Clinics*, vol. 23, pp. 8–14, 1988.

[3] *Statistics Canada*, 1992.

[4] Y. Setoguchi and R. Rosenfelder, Eds., *The Limb Deficient Child.* Springfield, MA: Charles C. Thomas, 1982.

[5] R. Sörbye, "Myoelectric prosthetic fitting in young children," *Clin. Orthopaed. Rel. Res.*, vol. 148, pp. 43–40, 1980.

[6] R. Sörbye, "Myoelectric controlled hand prostheses in children," *Int. J. Rehab. Res.*, vol. 1, pp. 15–25, 1977.

[7] N. Crone, "A comparison of myo-electric and standard prostheses—A case study of a pre-school aged congenital amputee," *Can. J. Occup. Ther.*, vol. 4, pp. 217–222, 1986.

[8] R. R. Caldwell, "A new myoelectric below elbow prosthesis for infants," *Orthot. Prosthet.*, vol. 39, pp. 72–74, 1985.

[9] S. G. Millstein, H. Heger, and G. A. Hunter, "Prosthetic use in adult upper limb amputees: a comparison of the body powered and electrically powered prostheses," *Prosthet. Orthot. Int.*, vol. 10, pp. 27–34, 1986.

[10] R. A. Roeschlein and E. Domholdt, "Factors related to successful upper extremity prosthetic use," *Prosthet. Orthot. Int.*, vol. 13, pp. 14–18, 1989.

[11] R. B. Stein and M. Walley, "Functional comparison of upper extremity amputees using myoelectric and conventional prostheses," *Arch. Phys. Med. Rehab.*, vol. 64, pp. 243–248, 1983.

[12] P. Herberts, L. Körner, K. Caine, and L. Wensby, "Rehabilitation of unilateral below-elbow amputees with myoelectric prostheses," *Scand. J. Rehab. Med.*, vol. 12, pp. 123–128, 1980.

[13] S. Hubbard, H. R. Galway, and M. Milner, "Myoelectric training methods for the preschool child with congenital below-elbow amputation: A comparison of two training programmes," *J. Bone Joint Surg.*, vol. 2, pp. 273–277, 1985.

[14] D. G. Shurr and T. M. Cook, *Prosthetics & Orthotics.* East Norwalk, CT: Appleton & Lange, 1990.

[15] D. F. Lovely, D. Stocker, and R. N. Scott, "A computer-aided myoelectric training system for young upper limb amputees," *J. Microcomp. App.*, vol. 13, pp. 245–259, 1990.

[16] D. F. Lovely, T. W. Hruczkowski, and R. N. Scott, "Computer aided myoelectric training," in *Proc. IEEE Eng. in Medicine & Biology Soc. 10th Annu. Int. Conf.*, vol. 10, 1988, pp. 1560–1561.

[17] W. F. Sauter, R. Dakpa, E. Hamilton, M. Milner, and R. Galway, "Prosthesis with electric elbow and hand for a three-year-old multiply handicapped child," *Prosthet. Orthot. Int.*, vol. 9, pp. 105–108, 1985.

[18] R. Soerjanto, "Myoelectric training of congenital below-elbow stumps in children," Progress Rep. 4, Inst. of Med. Phys., Da Costakade 45, Utrecht, The Netherlands, pp. 18–22, 1974.

[19] J. W. Michael, "Upper limb powered components and controls: Current concepts," *Clin. Prosthet. Orthot.*, vol. 10, pp. 66–67, 1986.

[20] L. M. Hermansson, "Structured training of children fitted with myoelectric prostheses," *Prosthet. Orthot. Int.*, vol. 15, pp. 88–92, 1991.

[21] M. Misfud, *Optimizing Myoprosthetic Management with Microcomputers Final Report for the Hospital for Sick Children Foundation.* Toronto: The Hugh MacMillan Rehabilitation Centre, pp. 1–106, 1990.

[22] W. K. Durfee, T. R. Mariano, and J. L. Zahradnik, "Simulator for evaluating shoulder motion as a command source for FES grasp restoration systems," *Arch. Phys. Med. Rehabil.*, vol. 72, pp. 1088–1094, 1991.

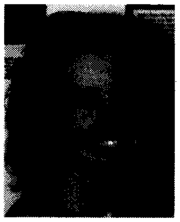
[23] B. T. Smith, M. J. Mulcahey, R. J. Triolo, and R. R. Betz, "Training tools for a neuroprosthetic hand system," in *Proc. RESNA 14th Annu. Conf.*, pp. 394–396, 1991.

[24] *Steeper Electric Prostheses Catalogue*, 1991.

[25] *Otto Bock Myobock Arm Components Catalogue*, 1986.

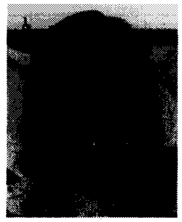
[26] Variety Ability Systems Incorporated, *Prosthetic Orthotic and Other Aids for the Disabled*, 1987.

[27] A. Van Lunteren, G. H. M. Van Lunteren-Gerritsen, H. G. Stassen, and M. J. Zuithoff, "A field evaluation of arm protheses for unilateral amputees," *Prosthet. Orthot. Int.*, vol. 7, pp. 141–151, 1983.



Anne-Caroline Dupont received the B.Sc. (Hon) degree in physics from McGill University in Montreal in 1990 and the M.Sc. degree in electrical engineering from Queen's University at Kingston in 1992 where she pursued her research in training and assessing child amputee clients in myoelectric control.

She currently resides in Gdynia, Poland where she is teaching physics and english as a second language.



Evelyn L. Morin received the B.Sc. degree in physiology from the University of Toronto in 1981; the M.Sc.E. degree in 1984 and the Ph.D. degree in 1988, both in electrical engineering, from the University of New Brunswick, where she pursued her research work at the Institute of Biomedical Engineering.

Since 1988, she has been an Assistant Professor in the Department of Electrical and Computer Engineering at Queen's University at Kingston, ON, Canada. She is a member of the EMBS and the Canadian Medical and Biological Engineering Society.