Is body powered operation of upper limb prostheses feasible for young limb deficient children?

J. SHAPERMAN*, M. LEBLANC**, Y. SETOGUCHI*** and D. R. MCNEAL*

**Rehabilitation Engineering Research Center on Technology for Children with Orthopedic Disabilities,
Rancho Los Amigos Medical Center, Downey, USA.*
**Rehabilitation Engineering Center, Packard Children's Hospital at Stanford, Palo Alto, USA.
***Child Amputee Prosthetics Project Shriner's Hospital for Crippled Children, Los Angeles, USA.

Abstract

The investigators measured efficiencies of body powered prehensors and cable control components of prostheses available for young children. Results indicated that the cable control systems and hook type prehensors have moderate to high efficiencies, but children's body powered hands have very low efficiencies. Measures of arm and shoulder strength of 3-5 year-old limb deficient children, both on the limb deficient and sound sides, were less than that reported in the literature for normal children. The findings were examined in relation to children's strength available compared with prosthesis strength requirements. The comparison demonstrates a way to establish measurable efficiency targets for new prehensor designs.

The article includes detailed findings on children's strength, and findings on efficiencies of the prehensors and cable control systems of children's upper limb prostheses. Sample calculations may be useful to future designers of body powered prehensors for young children. A more efficient body powered hand is especially needed. Preliminary calculations indicate that the use of currently available children's voluntary opening (VO), body powered hands is not feasible, given the low strength of young limb deficient children and the low efficiencies of the VO hands. The use of voluntary closing (VC) hands may be feasible but remains to be tested.

Introduction

Young children wearing body powered prehensors have difficulty gaining a firm grip on objects. Voluntary opening (VO) prehensors would give good grip if children were strong enough to overcome the resistance of strong rubber bands or springs. Voluntary closing (VC) prehensors would give good grip if children could sustain a strong muscle contraction over an extended period of time to hold the terminal device closed. Clinicians find that children can operate body powered prehensors well enough to get a good grip by the time they start kindergarten, but the infant and pre-school period is often frustrating for children because objects slip from the prehensors.

Researchers and clinicians have addressed the problem of poor grip force in several ways. One solution has been to develop body powered prehensors with features to enhance grip or reduce effort, such as CAPP I and Adept F.[1] These prehensors lessen the problem of poor grip, but many parents object to the appearance of a prehensor that does not resemble a hand. Another solution has been to fit young children with externally powered, myoelectrically controlled hands. These prehensors give very firm grip, but they are costlier, heavier and require more care and access to repair than body powered prehensors. Also, the geometry of the

All correspondence to be addressed to Julie Shaperman, Rehabilitation Engineering Research Center on Technology for Children with Orthopedic Disabilities, Los Amigos Research and Education Institute, Rancho Los Amigos Medical Center, 7503 Bonita Street, Downey, CA 90242, USA.

[1]CAPP Terminal Device, Size 1 is available from Hosmer-Dorrance Corp., 561 Division Street, PO Box 37, Campbell, CA 95008, USA. Adept prehensors are available from TRS, 1280-28th Street, Suite 3, Boulder, CO 80303-1797, USA.

small myoelectric hand does not accommodate many objects used in children's activities.

In the past, researchers have had little objective data on children's strength or prehensor grip strength requirements to use as targets in establishing design criteria for the development of body powered prehensors. Objective design criteria are highly desirable in solving the problem of poor grip.

The authors have conducted studies to identify and measure sources of inefficiency in the operation of children's body powered prehensors and measure children's body strength available for operation. The investigators compared available strength input with prehensor grip strength required (Fig. 1). The findings of the analysis are summarized in this article and will provide design criteria for development of a child's prehensor.

Review of the literature

The authors conducted an extensive review of the literature. Two studies reported objective measures of young children's arm and shoulder strength (Backman et al., 1989; Sykanda and Armstrong, 1989). One study reported efficiencies of body powered prehensors (Corin et al., 1987), and previously unpublished research reports provided data on control system efficiencies (Carlson and Long, 1988; LeBlanc, 1985). The reports contributed important information, but additional information was required to complete the analysis identified above. For example, the

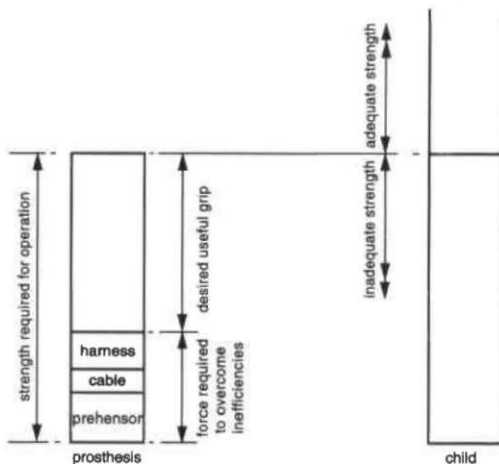STRENGTH AVAILABLE COMPARED WITH STRENGTH REQUIRED

Fig. 1. Strength available compared with strength required.

studies of children's strength were conducted on normal children and no studies were found which demonstrated that normative strength standards could appropriately be applied to children with limb deficiencies. The report of Corin et al. (1987) on prehensors did not include all currently available children's prehensors. No studies were found that reported on efficiency of the harness or suggested any way of measuring it. Also, no studies were found that analyzed the relationship between body strength available and prosthesis operating requirements. Finally, studies on children's needs for performing activities at various ages require considerable interpretation because grip strength in children's hands varies by type of grip. Also, factors besides measured grip strength make important contributions to secure gripping of objects.

Children's strength available for operation

Since young limb deficient children can perform gross play activities relatively well, and seem able to function almost normally, the investigators decided to compare strength of a small group of limb deficient children with published strength standards for children. Then, if limb deficient children's strength was within normal limits, published data could be used. A pilot study on arm and shoulder strength of 14 unilateral, congenital, trans-radial limb deficient children showed that limb deficient children were weaker than normal children on both the limb deficient and sound sides (Shaperman et al., 1992).

Method

Since published strength standards could not be used for limb deficient children, the investigators gathered new data by measuring arm and shoulder strength of 37 limb deficient children. All children (20 boys and 17 girls) had unilateral, congenital, trans-radial limb deficiencies and were 3, 4 or 5 years old. They came from three clinics in California. For consistency, the study was limited to children with unilateral, congenital, trans-radial limb deficiencies although the investigators recognize that children with higher level limb deficiencies also greatly need improved prehensors. Children younger than age three also greatly need firmer grip with body powered

Table 1. Description of the sample (N=37)

Age and sex						
Age (years)	3.0	3.5	4.0	4.5	5.0	5.5
Girls (N=17)	0	3	3	6	2	3
Boys (N=20)	5	3	3	2	2	5

Trans-radial limb deficiency			
Left	23	Short trans-radial	26
Right	14	Long trans-radial	11

Ethnic origin		Present prehensor	
Anglo	21	CAPP terminal device	19
Asian	0	Dorrance hook	1
Black	2	Mechanical hand	7
Hispanic	14	Myoelectric hand	5
		No prosthesis	5

prehensors, but it was not feasible to get valid measures of strength on children younger than age three. Table 1 lists the characteristics of the children in the study.

The investigators measured the strength in four motions that were considered potential sources of strength for prehensor operation: shoulder flexion (anterior motion of the humerus in the sagittal plane which represents both glenohumeral and axioscapular motion), shoulder abduction (lateral motion of the humerus in the frontal plane which represents both glenohumeral and axioscapular motion), shoulder (girdle) elevation (elevation of the scapula and clavicle measured in the frontal plane), and shoulder protraction (scapular motion away from the spinal column measured in the sagittal plane at the tip of the acromion). Procedures for measurements followed muscle strength measurement protocols reported in the literature by investigators who measured and reported strength of normal children (Sykanda and Armstrong, 1989). Measurements were made using a portable electronic dynamometer with force transducer. This myometer shows peak force attained at each trial on a digital readout in kilograms. The manufacturer reports

accuracy of the myometer to ±0.3 kg of force*. The same therapist made all measurements, and restrained the children from using substitute motions during measurements. Children were seated in a straight chair and held in position with a posture vest. The therapist positioned the myometer on the distal end of the humerus for measures of shoulder flexion and abduction on the tip of the acromion for shoulder (girdle) elevation and on the anterior surface of the head of the humerus for shoulder protraction. Each measure was repeated three times with rest periods between trials.

Data analysis included consideration of the following variables: age, height, sex, current prehensor, strength of sound side compared with limb deficient side and single peak force measurement compared with mean of three maximum efforts.

Results

Age and sex: Findings on children's strength are reported by age, sex and side of limb deficiency in Tables 2 and 3. With few exceptions, boys were stronger than girls of the same age. On average, boys were between 0.7 and 1.9 kg of force stronger than girls of the same age, except in shoulder (girdle) elevation where differences reached 2.8 kg. Also, strength differences between boys and girls were more pronounced among five-year-olds than among three or four-year-olds.

Sound side versus limb deficient side: Examination of Tables 2 and 3 shows children were not consistently stronger on either the sound or limb deficient side. For each motion, each child's strength on the sound side and limb deficient side were compared. For the majority

*Kilogram force is used throughout this paper as the measuring instrument displayed in these units. 1 kilogram force is equivalent to 9.81 newtons.

Table 2. Mean strength of 4 motions of 37 unilateral trans-radial limb deficient children

Age	Shoulder flexion				Shoulder abduction				Shoulder girdle elevation				Shoulder girdle protraction			
	LD side		Sound side		LD side		Sound side		LD side		Sound side		LD side		Sound side	
	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls
3.0	3.0	–	3.2	–	2.7	–	2.9	–	4.4	–	4.0	–	3.9	–	3.7	–
3.5	3.8	2.6	4.0	2.9	2.8	2.4	3.1	3.1	4.2	4.6	4.0	3.9	4.0	2.7	3.7	3.5
4.0	3.9	3.4	4.5	4.1	3.6	2.7	3.9	2.8	5.3	4.4	5.1	4.6	4.3	3.3	4.7	3.1
4.5	4.1	2.9	6.0	3.3	3.9	2.9	4.6	3.2	5.7	6.2	6.7	4.9	4.4	4.2	4.8	4.2
5.0	5.4	3.4	5.8	3.6	5.4	3.3	4.8	3.2	6.3	6.1	7.1	5.0	5.1	4.3	5.8	3.0
5.5	4.9	3.9	5.0	4.0	4.8	4.7	5.2	4.4	8.5	6.8	8.7	5.9	6.9	4.7	6.1	5.0

Strength is in kilograms of force, Age is in years.

Table 3. Peak strength of 4 motions of 37 unilateral trans-radial limb deficient children

	Shoulder flexion				Shoulder abduction				Shoulder girdle elevation				Shoulder girdle protraction			
	LD side		Sound side		LD side		Sound side		LD side		Sound side		LD side		Sound side	
Age	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls
3.0	3.1	–	3.5	–	2.8	–	3.0	–	4.9	–	4.8	–	4.1	–	3.9	–
3.5	4.1	2.9	4.4	3.9	3.1	3.1	3.5	3.4	5.0	5.0	4.6	4.1	4.5	3.2	4.2	3.8
4.0	4.6	4.1	5.1	4.2	3.9	2.8	4.2	3.1	5.9	4.8	5.6	5.4	4.8	3.5	5.3	3.3
4.5	4.2	3.3	6.3	3.8	4.3	3.2	5.2	3.6	6.4	6.6	8.0	5.5	4.6	4.5	5.2	4.6
5.0	6.2	3.6	6.8	4.0	5.8	3.5	5.2	3.6	7.5	6.7	7.9	6.5	5.7	4.7	6.8	3.4
5.5	5.3	4.0	5.6	4.6	5.2	5.1	5.8	5.2	9.9	7.4	10.5	6.8	7.8	5.7	6.5	5.6

Strength is in kilograms of force, Age is in years.

of children, shoulder flexion and abduction were 10% stronger on the sound side, and shoulder (girdle) elevation and protraction were 10% stronger on the limb deficient side. Table 4 shows average differences in mean strength betweeen sound and limb deficient side for each motion.

Single peak force measure versus mean of three maximum efforts: Table 2 shows mean strength of three maximum trials and Table 3 shows peak strength achieved in all trials for each motion. The average of three maximum trials consistently was slightly lower than the single peak measure. Peak strength varied by approximately 0.5 kg from the mean of three maximum trials for most motions measured, but reached differences up to 1.8 kg for shoulder (girdle) elevation, especially among five year

Table 4. Differences in mean strength: sound/limb deficient side*

Motion	Stronger side	Average difference
Shoulder flexion	Sound side	0.5 kg or 10%
Shoulder abduction	Sound side	0.4 kg or 10%
Shoulder (girdle) elevation	Limb deficient side**	0.6 kg or 12%
Shoulder protraction	Limb deficient side	0.5 kg or 12%

* Findings reflect trends among a majority of the 37 limb deficient children in the study.
**Four and five year old boys were stronger on the sound side in shoulder (girdle) elevation.

olds. Table 5 is a summary of the differences between the single measure of peak strength and the average of three maximum trials. Although theoreticians usually consider the single peak measure more accurate than the mean of three maximum contractions, there is growing acceptance of the use of the mean of three maximum contractions because of its greater reliability (Magnussen *et al.,* 1990; Magnussen, 1993; Sapega, 1990; Hood and Forward, 1965).

Examination of Tables 2 and 3 shows that mean strength does not increase with age in an even, linear pattern. This may be due to the small sample size. Review of the findings on individual children in this study suggests that most children had a spurt in strength at the age of $4\frac{1}{2}$ to 5 years, but the effect is masked when data are aggregated to calculate means. The clearest picture of children's strength progression is shown in Table 6, where data are presented in percentiles. Findings for boys and girls are combined in Table 6 since boys and girls wear the same prehensors, and strength was measured to provide data for prehensor design criteria. The table is formatted in the same manner as pediatric growth charts. Finally, data from Table 6 are summarized in Table 7 so they are more convenient to use in the analysis.

Table 5. Peak strength versus average of three maximum trials: a summary of differences.
Amount that peak strength exceeded the mean of three maximum trials.

Motion	Side	Average kg	Difference Percent	Range of Differences kg	Percent
Shoulder flexion	Limb deficient side	0.3	10.3	0.1 to 0.8	3 to 21
Shoulder flexion	Sound side	0.6	13.6	0.2 to 1.0	2 to 34
Shoulder abduction	Limb deficient side	0.3	9.7	0.1 to 0.7	4 to 29
Shoulder abduction	Sound side	0.4	11.0	0.1 to 0.8	3 to 18
Shoulder girdle elevation	Limb deficient side	0.8	12.0	0.4 to 1.4	9 to 19
Shoulder girdle elevation	Sound side	0.9	16.0	0.2 to 1.8	5 to 30
Shoulder protraction	Limb deficient side	0.5	11.0	0.2 to 1.0	5 to 21
Shoulder protraction	Sound side	0.5	10.3	0.2 to 1.0	5 to 17

Table 6. Strength percentiles (kg) by children's age (years)

Sound side						Limb deficient side				
5th	25th	50th	75th	95th		5th	25th	50th	75th	95th
					Shoulder flexion Strength in kg					
2.2	3.1	3.5	4.0	5.2	3 years	2.2	2.6	2.6	2.9	4.4
2.6	3.5	4.4	5.0	6.8	4 years	2.3	2.7	3.1	3.5	4.7
2.6	3.5	4.6	5.6	6.2	5 years	2.5	4.0	4.4	5.5	6.7
					Shoulder abduction Strength in kg					
2.1	2.5	3.0	3.2	3.6	3 years	1.7	2.0	2.2	2.9	4.4
2.5	2.8	3.2	4.1	5.0	4 years	1.8	2.5	3.1	3.5	4.7
2.2	4.1	4.5	5.0	6.4	5 years	2.6	4.0	4.4	5.5	6.7
					Shoulder girdle elevation Strength in kg					
2.6	2.6	4.1	4.5	5.2	3 years	2.8	3.5	4.8	5.1	6.3
3.5	4.6	5.2	5.4	6.9	4 years	3.6	4.1	5.3	6.6	10.5
3.7	6.3	6.6	8.0	11.4	5 years	3.8	6.3	6.8	8.3	12.0
					Shoulder protraction Strength in kg					
2.0	2.6	3.9	4.2	5.6	3 years	2.1	3.1	3.8	4.0	4.4
2.4	3.3	4.1	5.1	5.7	4 years	2.5	3.3	4.1	4.7	6.2
2.4	5.0	5.5	6.0	7.1	5 years	3.7	4.7	5.1	6.1	8.4

On average, boys' strength was 16% greater and girls' strength was 11% less than percentiles shown.

Arm and shoulder strength of the 37 children in this study was similar to that reported for the 14 children in the pilot study, and was less than the strength standards reported for normal Canadian and Scandinavian children (Backman *et al.,* 1989; Sykanda and Armstrong, 1989). Comparison of strength of the 37 limb deficient children with 33 normal five year olds from the same locale showed that the strength of the limb deficient children compared more favourably with a normal population (Baldwin and Priete, 1992). The strength data gathered directly from limb deficient children was used in calculations related to operation of children's body powered

prehensors in the following sections of this report.

Related studies

A pilot study was conducted in the pathokinesiology laboratory at Rancho Los Amigos Medical Center to learn how much of a child's strength is actually used to operate a body powered prehensor. A seven year old child with body powered trans-radial prosthesis exerted 50% to 100% of her maximum available muscle force when operating her CAPP I prehensor (exact percentage of maximum force varied for specific muscles).

Table 7. A summary of children's strength for operation of body powered prehensors

Age	Force available (kg)			
	Shoulder flexion	Shoulder abduction	Shoulder girdle elevation	Shoulder girdle protraction
3 years	3	2½ to 3	4 to 4½	2½ to 4
4 years	3 to 4	3 to 4	4½ to 6½	3½ to 4½
5 years	3½ to 5½	3 to 5½	6 to 8½	4 to 7

Ranges based on mean of three maximum contractions on limb deficient side.

An adult male with body powered trans-radial prosthesis used 50% or less of his maximum available muscle force for hook operation in a similar assessment (McNeal and DeRuyter, 1994). This finding supports observations that young children require more strength than they have available for prehensor operation, and it suggests that a new child's prehensor should require less than the maximum strength levels shown in Tables 6 and 7 if it is to give better grip than current prehensors.

Another study investigated whether a home-supervised activity programme would be effective for increasing arm and shoulder strength among 3-5 year old limb deficient children. The study followed 23 children over a one year period. Results showed that good compliance with the home activity programme was associated with increased strength beyond that which would be expected from growth and maturation alone, but the effect was still not large enough to compensate for the high operating force requirements associated with good grip in today's body powered prehensors.

Upper-limb prosthesis strength requirements
Sources of prosthesis inefficiencies

The prosthesis can be viewed as a system with three parts which contribute to the overall inefficiency: (1) the prehensor mechanism itself, (2) the cable and housing which transmit force from the harness to the prehensor, and (3) the harness which transmits force from the body to the cable.

Prehensors: The efficiencies of five body powered prehensors commercially available for young children are summarized in Table 8 (LeBlanc *et al.,* 1992). The efficiency of the prehensor (EP) equals the ratio of work out at the prehensor finger tips divided by the work into the prehensor at the distal cable. The efficiency of the prehensor (EP) factor accounts for the losses due to friction in the prehensor mechanism.

Cable and housing control system: The efficiencies of various types and combinations of cable and housing control systems have been calculated by Carlson and Long (1988) (Fig. 2) and by LeBlanc (1985). The efficiency for trans-radial prostheses using plastic cable and steel housing with plastic liner is about 90%. For this analysis, the measured efficiency of the cable (EC) is the ratio of force out of the cable housing divided by force into the cable housing.

Harnesses: The authors reviewed the literature, consulted with other researchers in the field, contemplated how to measure the efficiencies of harnesses, and decided that it is not feasible to do so within the constraints of this project. It is feasible to measure relative differences between harnesses, but it is difficult to measure the absolute efficiencies of harnesses. For this analysis, the estimated efficiency of the harness (EH) is assumed as the ratio of the force out of the harness to the proximal cable divided by the force into the harness provided by body motion.

Ratio of prehension force to cable force

The geometry of prehensors determines this ratio. For instance, the length of "thumb" lever arm to which the cable is attached on the Hosmer 10X hook is 4.45 cm. The length of the fingers is 6.35 cm to the point of prehension. The ratio of these two lengths (4.45/6.35) or 0.70 is the ratio of the prehension force to the prehensor cable pull force. If one pulls on the thumb with 4.55 kg of cable force, the prehension force at the finger tips will be 3.18 kg. This prehensor ratio (PR) will vary with the geometry of each prehensor and assumes 100% efficiency.

Estimation of prehension force available

The ultimate prehension force which a child will be able to achieve with a prosthesis is determined by the maximum measurable force which the child can generate minus the effects of the efficiencies and ratios listed above

Table 8. Efficiencies of five body powered prehensors

Prehensor	Work efficiency*
CAPP I (regular spring)	68%
Hosmer 10X hook (two bands)	82%
Steeper 2.0 hand	25%
NYU child size hand	27%
Adept F III	**

* Work efficiency is the ratio in percentage of the work output of each prehensor divided by the work input required for operation. In this case, work efficiency rather than force efficiency is used to take into account the effect of varying cable excursion.
** The Adept is a voluntary closing (VC) prehensor and work efficiency cannot be compared in the same way as for the four voluntary opening (VO) prehensors.
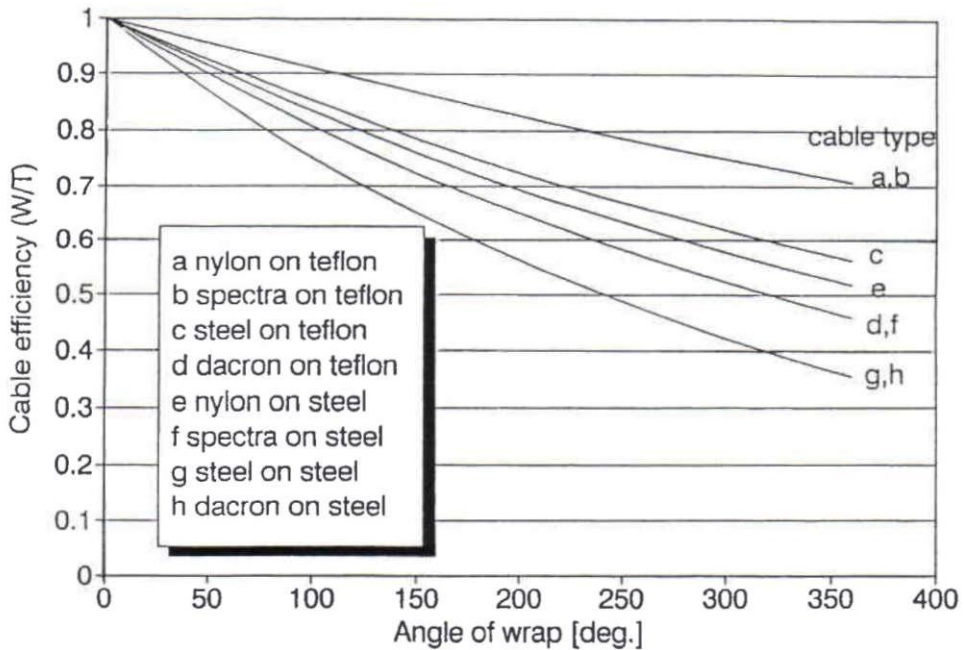
Fig. 2. Cable efficiency.

according to the formula below.

Prehension force (PF) = maximum force (MF) x efficiency of the harness (EH) x efficiency of cable/housing (EC) x efficiency of prehensor (EP) x prehensor ratio (PR).

Table 9. Prehension force/maximum force for children's prehensors

Prehensor	Prehension force/maximum force
CAPP I (regular spring)	26%
Hosmer 10X (two bands)	46%
Steeper 2.0 hand	12%
NYU child's hand	10%
Adept	50%*

* Assuming a 95% VC prehensor efficiency.

Using a Hosmer 10X with two rubber bands on a trans-radial prosthesis as an example:

EH = 90% unknown but liberally assumed to be high
EC = 90% measured
EP = 82% measured
PR = 70% measured
Then PF = MF X 90% x 82% x 70% = MF x 46%

If the MF a child can generate is 4.55 kg, then the PF to be expected is 2.1 kg.

Taking the measured values for all five prehensors and making the assumptions as in the above example, the relationships are shown in Table 9.

Strength requirements

Using the previous calculations for VO

Table 10. Calculated prehension force available given children's strength available for operation

Prehensor	Preh Force/ Max Force Percentage*	Max Force Available (kg)			Calculated Preh Force (kg)			Desired Preh Force (kg)			Calculated PF/ Desired PF Percentage		
		3 yrs	4 yrs	5 yrs	3 yrs	4 yrs	5 yrs	3 yrs	4 yrs	5 yrs	3 yrs	4 yrs	5 yrs
CAPP 1 (reg spring)	26%	3.1	3.8	5.0	0.8	1.0	1.3	1.8	1.8	1.8	45%	54%	72%
Hosmer 10X (2 bds)	46%	3.1	3.8	5.0	1.4	1.7	2.3	1.8	1.8	1.8	80%	95%	128%
Steeper 2.0 VO	12%	3.1	3.8	5.0	0.4	0.5	0.6	1.8	1.8	1.8	21%	25%	33%
NYU Hand	10%	3.1	3.8	5.0	0.3	0.4	0.5	1.8	1.8	1.8	17%	21%	28%
Adept	50%	3.1	3.8	5.0	1.6	1.9	2.5	1.8	1.8	1.8	87%	104%	139%

*Maximum force available is calculated from the average of shoulder flexion and shoulder protraction as listed in Table 7. These are the two body control motions usually used for figure of 8 harnesses.
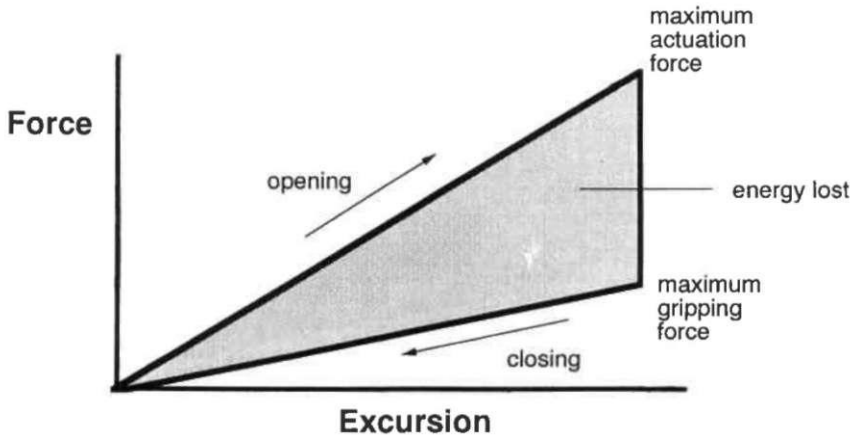
Fig. 3. Efficiency of voluntary opening prehensor.

prehensors and a prehensor force/cable force ratio of 70%, the prehensors compare as shown in Table 10. Calculations indicate the prehension grip which can be expected given the measured strength the children have for operation.

Table 10 refers to desired prehension force as 1.8 kg based on an early study of grip force needed to hold objects used by children at ages 2-5 years (Gottlieb, 1954). Desired grip force factors are explored further in another publication (Shaperman and LeBlanc, 1995).

Inherent differences in efficiency between VC and VO prehensors are shown in Figures 3 and 4. With VO prehensors, the amputee must exert force to overcome the grip force of the closing spring. As noted in Table 8, currently

available hands have lower efficiencies than "non-hands". VO prehensors have low efficiencies and resultant low grip force, and hands are especially inefficient. This leads one to consider the option of the development of VC hands which are inherently more efficient.

Discussion
Practical assessment of the formula to estimate prehension force

In the text above, the authors propose a formula for estimation of prehension force (PF = MF x EH x EC x EP x PR). A practical test was performed to find out how close this formula would come to actual measures in a clinical setting. In this test, PF and MF were measured on 3 five year old limb deficient
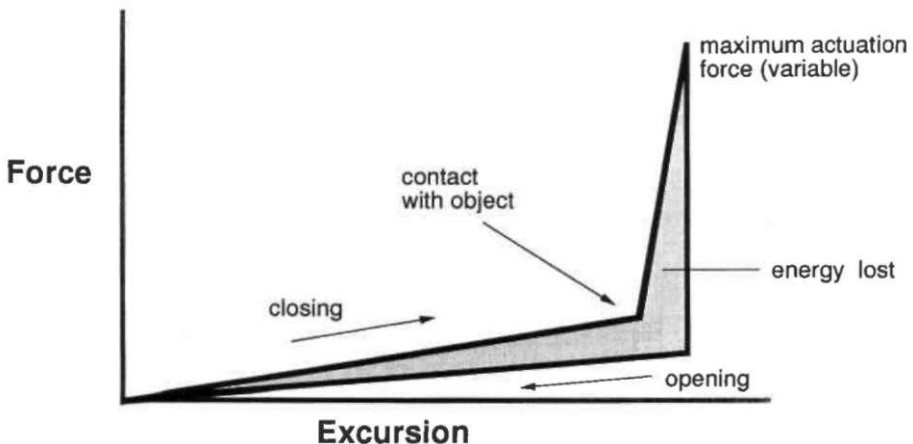

Fig. 4. Efficiency of voluntary closing prehensor.

children using the CAPP I voluntary opening prehensor. Then, PF divided by MF should produce an efficiency factor as shown in Table 9. In the test which was carried out, PF was measured using a specially designed bracket to hold the thumb tip of the CAPP I next to a pinch meter which recorded how strongly the child could push the prehensor open against the meter. MF was measured by averaging strength of shoulder flexion and shoulder protraction. Strength was measured with a myometer. According to Table 9, the expected PF/MF ratio for CAPP I with a regular spring is 26%. However, the children were using the soft spring with a PF/MF ratio of 28%. The three subjects achieved PF/MF ratios of 37%, 49% and 54%. All of these are higher than the expected ratio. The reason for the difference may be that averaging strength of two anatomically measured motions is not an exact representation of the amount of force children exert when performing the control motion. The result might also differ if the actual efficiencies of components of the children's prostheses differ from the estimates in the model. Considering these possibilities, it is likely that the formula gives a conservative estimate of prehension force. Possibly, the outlook is more positive than might be anticipated for developing a body powered prehensor that children can comfortably operate and that gives good grip.

Children's strength available for operation

A child cannot exert maximum muscle force and sustain it for a long time. The usable or sustainable force is less than maximum. Studies have shown that muscle action at 15% to 20% of maximum is the level at which repeated muscle action can occur over time without fatigue (Monod, 1985). For intermittent activity, such as using prostheses, the ratio observed by preliminary testing in the pathokinesiology laboratory study was 50%. The usable to maximum force ratio for prosthesis use is not scientifically documented and was not used for calculations of estimated grip force in the formula above. If muscle strength data is used to establish design criteria for a child's prehensor, it is important to consider this limitation. This is especially relevant to VC prehensors where sustained force must be applied for holding objects.

Upper limb prosthesis strength requirements

At the meeting of the Advisory Group to this project on 19 May, 1993, it was the strong opinion of parents and professionals that hooks and non-hand prehensors are no longer acceptable to patients and that hands are the prehensors of choice for future development. The Steeper and NYU hands are the only body powered hands presently commercially available for young children and the prehension force/maximum force ratio is very low for each. The efficiencies of the VO hands and the resultant grip forces achievable are very low. For children to achieve a usable grip force requires a very high body force input which they simply do not have. Current VO hands do not appear to be feasible for practical use by young children.

The efficiencies of VC hands are theoretically much higher and give correspondingly higher grip forces than for VO hands for the same force input. However, the authors still are not sure if children have sufficient body power to effectively operate VC hands. The calculations made in this paper must be confirmed by testing. Also, VC prehensors in general have two problems which must be solved for them to be clinically useful: (1) VC prehensors stay open when not in use – which looks awkward and the thumb and fingers can catch on objects; (2) Cable force must be maintained on VC prehensors when grasping and holding an object to keep from dropping it.

Questions for further study

Some of the findings of this study raise questions that may be relevant to future research:

(1) How is upper limb strength influenced by wearing a body powered prehensor compared with using a myoelectric limb or no prosthesis at all? In this study, only five children have myoelectric limbs and five others have no prosthesis. Strength of children in each of these groups was compared with strength of the 27 children with body powered prehensors. All of the children with no prostheses were weaker than wearers of body powered prehensors in shoulder flexion and abduction on the limb deficient side, but the differences were less clear when comparing strength of shoulder (girdle) elevation and protraction. Conclusions cannot be drawn from the small number of

children in the two sub-groups, but finding suggest that further investigation may be worthwhile.

(2) Can young children be helped to increase arm and shoulder strength so they will be better able to get good grip with available body powered prehensors? The home supervised activity programme conducted in conjunction wtih this study did not increase strength enough to improve grip with prehensors, but studies using other interventions might be more successful for increasing strength.

(3) Shoulder flexion is a relatively weak motion. Can ways be found to harness alternate motions with greater strength to serve as power sources for prosthesis operation? Possibly, an entirely different harness design could be created to use shoulder (girdle) elevation alone or in combination with other motion(s). Although the standard system works well for adults, the difficulty children have in using shoulder flexion for prosthesis operation suggests that a new look at ways to harness sources of greater strength may be highly beneficial for them.

(4) Can the data from this study be used to estimate strength of two year old limb deficient children even though their strength cannot directly be measured? Since two year olds have the greatest difficulty getting good grip with body powered prehensors, knowing their strength is important in establishing design criteria for a new body powered prehensor. If it is assumed that strength at age two is related to strength at a later age, and that no strength spurt occurs between age two and age three, the strength of two year olds may be roughly estimated through graphic analysis of percentile data presented in Table 6. This analysis suggests that two year olds at the 50th percentile for strength have the following forces available: shoulder flexion = 2.8 kg, shoulder abduction = 1.4 kg, shoulder (girdle) elevation = 4.0 kg, and shoulder protraction = 3.8 kg. Another important factor to consider besides strength of two year olds is that lower development levels of coordination and cognition may lessen their ability to use their available strength effectively.

(5) How much grip strength does a child's prehensor have to provide? Studies on strength of normal children's hands show that three year olds have full hand grip strength up to 4.3 kg

(Brown, 1973), but studies of grip force needs in children's prehensors suggest that as little as 1.8 kg is sufficient for most activities performed by three year olds (Gottlieb, 1954). Grip may be enhanced by factors such as friction, resilience of grasping surfaces (such as soft tissues of human hands), and prehensor geometry (such as opening span, depth and shape of grasping area). These factors are important to the extent that they may offset the need for high grip force. Children with myoelectric hands appear to use the strong grip force these prehensors provide to compensate for deficiencies in prehensor geometry. The myoelectric experience has not demonstrated that prehensors must provide very high amounts of grip force in order to hold objects securely.

Conclusions

Although clinicians treating young children with unilateral trans-radial and trans-humeral deficiencies have accepted the concept of early prosthetic fitting, the body powered prehensors available for these children provide poor grip force. New voluntary opening (VO) prehensors, such as CAPP I and voluntary closing (VC) prehensors such as the Adept have been developed to try to improve prehensile function. Today's body powered hands require high operating forces and do not give young children good grip. The enthusiasm for myoelectric hands has been partly due to the need for improved grip, and also for cosmesis.

The purpose of this study was to analyze inefficiencies in body powered prostheses for young children, and to learn whether problems in children's strength prevent them from obtaining maximum function from prostheses. Studies have shown:

(1) Conventional trans-radial systems are relatively efficient, except for body powered hands. The use of today's voluntary opening hands does not appear feasible for young, limb deficient children. VC hands are inherently more efficient, and may be feasible, but this supposition needs to be tested. The major target for improvement is mechanical hands and their cosmetic gloves.

(2) Child amputees have less strength in the limb deficient arm than normal children, thereby making operation a bigger challenge. These findings indicate a need to consider ways of designing a body powered prehensor with

better prehensile function. Studies of effects of friction, resilience and geometry of prehensors might provide better contact with objects to reduce the need for high grip forces. Design criteria have been established for developing a hand with sufficient grip to meet the needs of young limb deficient children.

REFERENCES

BACKMAN E, ODENRICK P, HENRIKSSON KG (1989). Isometric muscle force and anthropometric values in normal children aged 3-5 and 15 years. *Scand Rehabil,* **21,** 105-114.

BALDWIN K, PREITE G (1992). Isometric shoulder strength of the normal five-year-old. Unpublished Masters Project – Los Angeles: University of Southern California, Department of Physical Therapy.

BROWN WC, (1989). A study of the strength capabilities of children ages two through six. *National Technical Information Service, US Department of Commerce,* COM-73-11286.

CARLSON L, LONG M (1988). Quantitative evaluation of body powered prostheses. *Modelling and Control Issues in Biomechanical Systems.* American Society of Mechanical Engineers. DSC-Vol **12,** BED-Vol **11,** 1-16.

CORIN JD, HOLLEY TM, HASLER RA (1987). Mechanical comparison of terminal devices. *Clin Prosthet Orthot* **2**(4), 235-244.

GOTTLIEB M (1954). Force and excursion requirements for the child's prehension device. *Special Technical Report 21.* – Los Angeles: University of California, Department of Engineering, Artificial Limb Research. p1-28.

HOOK LB, FORWARD EB (1965). Strength variations in two determinations of maximal isometric contractions. *J Am Phys Ther Assoc,* **45,** 1046-1053.

LEBLANC M (1985). Evaluation of cable vs. hydraulic transmission of forces for body powered arm prostheses. In: RESNA '85; *proceedings of the Eighth Annual Conference on Rehabilitation,* Memphis, Tennessee, June 24-28, 1985. – Washington, DC: RESNA.

LEBLANC M, SETOGUCHI Y, SHAPERMAN J, CARLSON L. (1992). Mechanical work efficiencies of body powered prehensors for young children. *J Assoc Child Prosthet Orthot Clin* **27,** 70-75.

MAGNUSSON SP (1993). Clinical strength testing. *Rehabil Management* December-January, **38-45,** 123.

MAGNUSSON SP, GLEIN GW, NICHOLAS JA (1990). Subject variability of shoulder abduction strength testing. *Am J Sports Med* **18,** 349-353.

MCNEAL DR, DERUYTER FD (1994). Annual Report: Rehabilitation Engineering Research Center on Technology for Children with Orthopedic Disabilities. – Downey, CA: *Los Amigos Research and Education Institute.* p2-5.

MONOD H (1985). Contractility of muscle during prolonged static and repetitive dynamic activity. *Ergonomics* **28,** 81-89.

SAPEGA AA (1990). Muscle performance evaluation in orthopedic practice. *Bone Joint Surg* **72A,** 1562-1574.

SHAPERMAN J, LEBLANC M (1995). Prehensor grip for children: a survey of the literature. *J Prosthet Orthot* **7**(2), 61-64.

SHAPERMAN J, SETOGUCHI Y, LEBLANC M (1992). Upper limb strength of young limb-deficient children as a factor in using body powered terminal devices: a pilot study. *J Assoc Child Prosth Orthot Clin* **27,** 89-96.

SYKANDA AM, ARMSTRONG RW (1989). Measurement of muscle strength: development of norms in children of school age using the myometer. Unpublished report. Vancouver, BC, Canada: British Columbia Children's Hospital.