Disability and Rehabilitation: Assistive Technology, November 2007; 2(6): 346 – 357

RESEARCH PAPER

Consumer design priorities for upper limb prosthetics

ELAINE BIDDISS[1], DORCAS BEATON[2] & TOM CHAU[1]

[1]*Bloorview Research Institute, Toronto, Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, and* [2]*The Institute for Work and Health, Toronto, Ontario, Canada*

Accepted October 2007

Abstract

Purpose. To measure consumer satisfaction with upper limb prosthetics and provide an enumerated list of design priorities for future developments.

Methods. A self-administered, anonymous survey collected information on participant demographics, history of and goals for prosthesis use, satisfaction, and design priorities. The questionnaire was available online and in paper format and was distributed through healthcare providers, community support groups, and one prosthesis manufacturer; 242 participants of all ages and levels of upper limb absence completed the survey.

Results. Rates of rejection for myoelectric hands, passive hands, and body-powered hooks were 39%, 53%, and 50%, respectively. Prosthesis wearers were generally satisfied with their devices while prosthesis rejecters were dissatisfied. Reduced prosthesis weight emerged as the highest priority design concern of consumers. Lower cost ranked within the top five design priorities for adult wearers of all device types. Life-like appearance is a priority for passive/cosmetic prostheses, while improved harness comfort, wrist movement, grip control and strength are required for body-powered devices. Glove durability, lack of sensory feedback, and poor dexterity were also identified as design priorities for electric devices.

Conclusions. Design priorities reflect consumer goals for prosthesis use and vary depending on the type of prosthesis used and age. Future design efforts should focus on the development of more light-weight, comfortable prostheses.

Keywords: *Upper extremity, limb prosthesis, prosthesis fitting, prosthesis design, rehabilitation*

Introduction

Consumer feedback is vital to the successful development of products and services that address user wants and needs [1 – 4]. In the area of upper limb prosthetics, it is particularly valuable in tracking satisfaction with state-of-the-art developments, and in guiding research efforts [5,6]. A number of consumer surveys have explored aspects of this topic in the past, particularly with regards to factors in prosthesis use and rejection [7 – 12]. Most notably, Kejlaa (1993) [13] and Atkins et al. (1996) [6] documented areas of dissatisfaction and priorities for future design. More recently, Pons et al. (2005) [14], reported on the concerns of individuals with traumatic limb loss specifically. Localized studies have also been conducted with regards to desired developments and user satisfaction by both Kyberd et al. (1998) in adults [5], and Routhier et al. (2001), amongst others, in pediatrics [15 – 22]. Other studies have focused on the specific needs of developing nations and/or on variations in cultural perspectives [23 – 26]. For an exhaustive overview of prosthesis satisfaction and use, the interested reader is referred to Biddiss and Chau [27].

This study is motivated by the need for up-to-date, comprehensive assessment of consumer satisfaction and design priorities. The impact of recent technological advancements (e.g., life-like silicone gloving, light-weight power sources, microprocessor technologies) in addition to social developments (e.g., extended funding policies) remains largely unknown [28]. Likewise, the distinctive design priorities of pediatric and adult populations, and wearers of different types of prostheses, require clarification. Lastly, insights provided through qualitative comments and reflections have yet to be expressly used in the definition of consumer priorities [6]. In

Correspondence: Tom Chau, Bloorview Research Institute, 150 Kilgour Road, Toronto, ON, M4G 1R8. Canada. Tel: +1 416 425 6220 ext 3515. Fax: +1 416 425 1634. E-mail: tom.chau@utoronto.ca

ISSN 1748-3107 print/ISSN 1748-3115 online © 2007 Informa UK Ltd.
DOI: 10.1080/17483100701714733

response to these limitations, this study explores varying consumer design priorities through a mixture of quantitative and qualitative data. Specifically, the objectives of this study are threefold:

(1) To contextualize participants with respect to demographics, history of wear and functional goals for prosthesis use;
(2) To measure consumer satisfaction with specific attributes of prosthesis design relating to appearance, comfort, function, control, durability, and cost; and
(3) To present consumer design priorities delineated by prosthesis type (electric, body-powered, or passive) and age (pediatric or adult).

Methods

The questionnaire

A consumer questionnaire was developed to explore prosthesis use and satisfaction. A number of prominent researchers and clinicians (see Acknowledgements) along with several individuals with upper limb absence were consulted in the development and pilot testing of this questionnaire. In addition to basic demographics (e.g., age, level/origin of limb absence), the survey collected data on prosthesis history, functional needs, satisfaction, and design priorities. Data were collected through a mixture of closed and open-ended questions as summarized in Table I.

Target population and sampling strategies

The survey was targeted towards individuals with upper limb absence regardless of level and origin of limb absence or age. Children under the age of 12 were accessed through parents/guardians. Both users and past users of all types of prosthetic devices were encouraged to participate. The questionnaire was available in four languages (English, Spanish, French, and Dutch) and was accessible in paper format and online. Potential limitations and consequences of online distribution are outlined in the discussion section.

The following precautions, as recommended in previous studies [29], were adopted to monitor sampling and online data collection:

(a) Local collaborators were enlisted to enable recruitment through a trusted source (i.e., a support group or a rehabilitation centre) in an effort to mitigate non-response due to spam filtering or incorrect mailing addresses. Respondents were asked to specify the organization through which they were recruited;
(b) Where possible, pre-notification (e.g., mailed flyers, email or telephone call) was undertaken to increase response rates;
(c) A well-established web provider (www.vovici.com) was employed to host the survey and to limit system incompatibilities, such as those introduced by browser settings. The survey was available in paper format to reduce sampling bias;
(d) The Internet Protocol (IP) address was used to identify and filter repeat respondents;
(e) Responses were screened for data completeness and internal consistency using information patterns (e.g., series of dates, detailed descriptions of limb absence and prosthesis components) in an effort to filter false respondents;
(f) Participant demographics were meticulously collected within the survey in an effort to contextualize the sample population and identify possible biases.

The survey was circulated through a number of online support groups (i.e., Arm-Amp, I-CAN, Stumps R Us, UpperEx), healthcare providers (i.e., Bloorview Kids Rehab, Canada; Shriners Hospital for Children in Los Angeles, USA; Sint Maartenskliniek, The Netherlands) and was promoted on the Otto Bock Inc website, a prominent manufacturer of upper limb prostheses. The sample group was self-selected. The questionnaire and study methodology were approved by science and ethics boards at Bloorview Kids Rehab and the University of Toronto.

Data analysis

Quantitative data were analyzed using SPSS 15.0 statistical software. Mean rankings were compared using the Friedman test. Chi-squared analysis was applied to comparisons of categorical groups while differences in ordinal ratings (i.e., satisfaction, design priorities, etc.) were evaluated using the Mann-Whitney U Test (for 2 groups) or the Kruskal-Wallis test (for more than 2 groups). Frequency counts and three measures of central tendency (mean, median, and mode) were used where appropriate.

Qualitative data were organized using NVivo 7 and consisted of: (a) Consumer-specified design priorities (in list format); (b) improvements desired from prosthesis development (detailed description); and (c) activities found to be challenging in everyday life (detailed description/list format). Listed items were subjected to content analysis and weighted-frequency counts. Specifically, design priorities, as indicated by consumers asked to rank their top five specific requests for prosthesis development, were quantified using a weighted rank-sum approach.

Table I. Summary of survey design by topic, number and types of questions, and primary factors of interest.

Topic	No. and type of questions	Relevant factors
Participant demographics	7 - Categorical 1 - Likert 2 - Numerical	Level of limb loss Length of residua Origin of limb loss Dominant hand involvement Gender Frequency of associated medical conditions and pain Year of birth Year of amputation
Personal views on prostheses	1 - Ordinal 1 - Likert 1 - Multiple choice	Prosthesis design priorities Perceived need for a prosthesis User status
Past prosthesis usage and reasons for non-wear	1 - Categorical 1 - Likert 3 - Multiple choice 3 - Numerical 2 - Open-ended	Past prosthesis use Views on future prosthesis use Reasons for non-wear Challenges encountered in daily life
Prosthesis usage and satisfaction	3 - Categorical 11 - Likert 3 - Ordinal 14 - Multiple choice 4 - Numerical 4 - Open-ended	Time of fitting Past prostheses Current prostheses Views on future prosthesis use Primary prosthesis Model/manufacturer of primary prosthesis Technical characteristics of primary prosthesis (e.g., control strategy) Cost of prosthesis and repairs/maintenance Frequency of maintenance Personal involvement in prosthesis selection Selection factors Frequency of wear Activities for which worn Functional use Satisfaction (i.e., appearance, function, durability, comfort, and cost) Detailed design priorities Use of secondary prostheses Reasons for non-wear Challenges encountered in daily life
Qualitative experiences	1 - Multiple choice 2 - Open-ended	Suggestions for future prosthesis development Additional comments/feedback

Specifically, a priority score (P_d) was calculated for the dth design consideration according to Equation 1.

$$P_d = \frac{\sum_{r=1}^{5} (6-r)\cdot f_d(r)}{5\cdot N} \times 100 \qquad (1)$$

where N represents the number of participants in the group of interest, $f_d(r)$ is the frequency with which the dth design concern was given a ranking, $r \in \{1,2,\ldots 5\}$ with $r=1$ denoting the highest design priority. Design concerns that are frequently considered the first priority will incur high values of P_d. The denominator of Equation 1 is simply a normalizing factor to enable comparisons between groups of users of different devices (e.g., passive, body-powered, and electric) and is established as the maximum possible score that any one design concern could achieve if given a rank, $r=1$, by all N participants in the group of interest. Pd is multiplied by 100 to yield a range from 0 to 100 for ease of interpretation. To analyze the functional challenges encountered by respondents, common activities appearing on self-reported lists of challenges were tabulated and frequency counts were calculated. Lastly, emergent themes in the areas of: (1) Functional needs, (2) design priorities, and (3) overall perspectives on prosthesis technology, were documented and expressed through representative quotations.

Results

Sample population demographics

A total of 266 respondents completed the anonymous survey from which 242 were included in this study (i.e., in total, 24 responses were discarded on the basis of repeated IP address and similarity of data [3 respondents]; incompleteness or inconsistency of data [7 respondents]; ineligible limb absence [5 respondents]; and underage [9 respondents]). The average age of the pediatric group ($n = 97$) was 9.5 ± 6 years with a range of 1 – 18 years, while that of the adult population ($n = 145$) was 43 ± 15 years with a range of 19 – 80 years. Of pediatric responses, 70% were submitted by parents/guardians. Participants received rehabilitation primarily in the United States (43%), Canada (35%), and the Netherlands (11%). Levels of limb absence ranged from partial hand to forequarter disarticulation, with 16% of individuals reporting limb absence at or distal to the wrist, 54% reporting trans-radial limb absence, 21% trans-humeral, and 7% at shoulder level or higher. Trans-humeral limb absence was more common in adults (27%) than in children (11%), ($p = 0.003$), while trans-radial limb absence was more prevalent in pediatrics (64%) than in adults (47%), ($p = 0.009$). As expected, the occurrence of congenital limb absence was higher in pediatrics (91%), than in the adult population (41%), ($p < 0.001$). Bilateral limb absence was reported in 15% of cases and 51% of respondents were male. There were no significant differences between the adult and pediatric population in terms of gender, or type of limb absence (i.e., unilateral or bilateral).

Participants were advised of this survey through rehabilitation centres (52%), online support groups (39%), the Otto Bock website (3%), or through an internet search or family/friends (6%). The completion rate of the online survey (i.e., the number of surveys submitted divided by the number of times the survey was accessed) was 40%. Previous response rates for surveys addressing upper limb prosthesis design have ranged from 24% [6] for large-scale mailing campaigns to 69% [5] for sampling strategies using more localized and directed contact.

Prosthesis history and use

To characterize prosthesis history, participants were asked to indicate all devices tried in the past, all devices currently worn, the primary device (i.e., the most used prosthesis) and any devices of interest for future use. Rejection rates were calculated by dividing the number of individuals who no longer use the device in question (prosthesis rejecters in that category of device) by the number who had tried it at some point in the past. Those who have never worn a prosthesis are not included in rates of rejection. Table II presents the data compiled. The pediatric rate of rejection for passive hands (61%), which are often used as an introductory device, is significantly higher ($p = 0.03$) than the rate for active prostheses. In adults, body-powered hands have a significantly higher ($p < 0.02$) rate of rejection (65%) than electric hands (41%), body-powered hooks (51%) or passive hands (47%). Otherwise, there were no significant differences in rejection rates between device types in either age class. 21% of adults and 19% of children rejected prosthesis use entirely, while 67% of adults and 57% of children used a prosthesis on a regular basis (Figure 1). Electric hands spark the greatest interest for future use in both adult and pediatric populations.

Table II. Prosthesis rates of use and rejection.

Prosthesis	Currently used	Previously used	Rejection Rate	Primary Prosthesis	Interested in future use
Adults					
Passive hook	5	19	74%	2%	1%
Passive hand	33	62	47%	18%	10%
Body-powered hook	43	87	51%	32%	2%
Body-powered hand	15	43	65%	3%	3%
Electric hook	13	21	38%	3%	13%
Electric gripper	10	24	58%	1%	10%
Electric hand	58	98	41%	41%	26%
Other	11	19	42%	–	11%
None	–	–	–	–	25%
Pediatric					
Passive hook	2	3	33%	6%	0%
Passive hand	18	46	61%	23%	10%
Body-powered hook	12	23	48%	14%	2%
Body-powered hand	9	17	47%	15%	7%
Electric hook	0	0	–	0%	8%
Electric gripper	0	2	100%	0%	7%
Electric hand	27	42	36%	42%	33%
Other	5	14	64%	–	7%
None	–	–	–	–	26%

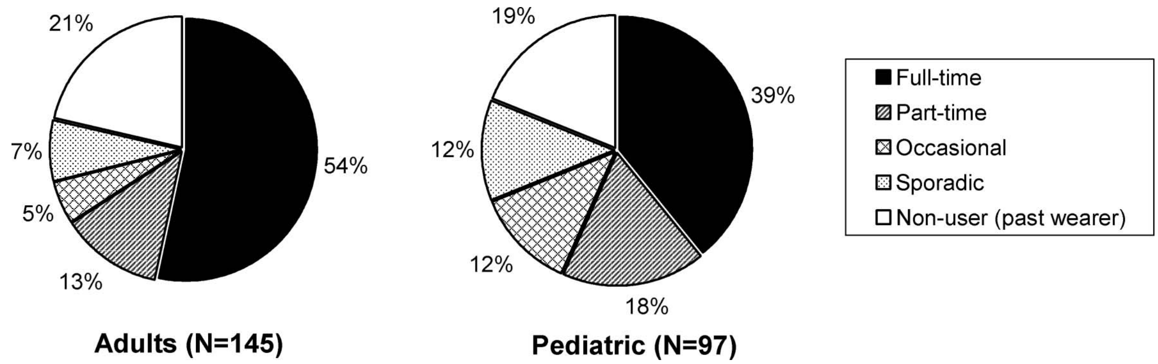

Figure 1. Prosthesis use in pediatric and adult populations.

A few significant observations were made with regards to prosthesis selection. Firstly, individuals with high level limb absence (i.e., above elbow) are more likely to choose a body-powered hook as opposed to an electric hand as the primary device ($p=0.003$), as are individuals with bilateral limb absence ($p=0.025$). Adults with congenital limb absence are more likely to wear a passive hand than those with acquired ($p < 0.001$). Body-powered hooks were more commonly used by adults than by children who tended to select hand-shaped terminal devices ($p=0.008$). Individuals in the United States used a higher proportion of body-powered hooks than those in Canada and The Netherlands ($p=0.007$). This observation also held for adult populations specifically ($p=0.035$). Gender is not statistically associated with the type of prosthesis worn. The type of primary prosthesis is not related to the extent of wear.

Goals of prosthesis use

To contextualize the goals and expectations associated with different prostheses, participants were asked to rank the importance of various design characteristics (Table III). Users of body-powered hooks and electric hands value function and comfort most highly, while users of passive hands ranked appearance and comfort at the forefront. Low cost was deemed more important to body-powered users than to those using passive or electric hands, while appearance was valued less.

Table IV indicates the importance of a range of functional roles in the design of a prosthesis as ranked by consumers of active and passive prostheses. In general, all prostheses, regardless of genre, were used functionally in daily life, particularly for steadying and stabilizing tasks.

Of interest are the specific tasks and activities found to be challenging by individuals with limb absence. Responses to an open-ended question on this topic were categorized and quantified in terms of the frequency with which each was reported (Table V). Interestingly, 16% of the 178 individuals who responded to this question had not encountered any insurmountable challenges in their daily life, while 10% of individuals found most activities, particularly bilateral tasks, to be challenging. The latter group consisted of a proportionately greater number of adults ($p=0.007$) with acquired limb absence ($p < 0.001$) at a higher level ($p=0.012$) than the former. Almost all individuals who reported a great number of challenges made use of a prosthesis to aid in their daily life, while users and non-users were equally represented in the group not experiencing challenges ($p=0.005$). No statistically

Table III. Design priorities of passive, body-powered and electric prosthesis users with rankings of importance (given in parentheses) as based on Friedman's Rank Test ($p < 0.001$).

Importance	Passive hand ($n=36$)	Body-powered hook ($n=46$)	Electric hand ($n=79$)
1	Comfort (2.00)	Function (2.07), Comfort (2.07)	Comfort (1.91)
2	Appearance (2.46)	Durability (3.25)	Function (2.39)
3	Function (3.06)	Cost (3.73)	Appearance (3.01)
4	Durability (3.31)	Appearance (3.89)	Durability (3.23)
5	Cost (4.18)		Cost (4.45)

Table IV. Consumer specified importance of functional roles for passive versus active prostheses with rankings of importance (given in parentheses) based on Friedman's Rank Test ($p < 0.001$).

Importance	Active prostheses ($n=151$)	Passive hands ($n=38$)
1	Gripping (2.42)	Appearance (2.35)
2	Steadying (2.52)	Steadying (2.55)
3	Manipulating (2.80)	Manipulating (3.28)
4	Appearance (3.14)	Gripping (3.38)
5	Body language (4.11)	Body language (3.44)

significant differences with respect to the type of prosthesis used or the gender of participants was observed.

Satisfaction with current prostheses

Participants were asked to rate their satisfaction for a number of aspects of prosthesis use and design (Table VI). Table VII lists the areas where dissatisfied or neutral (i.e., neither satisfied nor dissatisfied) feelings were reported for each type of prosthesis. Passive wearers did not report any areas of dissatisfaction, with neutral feelings in the areas of cost, function, glove staining, lack of sensory feedback, and temperature/perspiration control. The latter two items, along with harness comfort, grasp of soft or large objects, and grip strength, were areas of dissatisfaction for body-powered users. Electric wearers were also dissatisfied with heat/perspiration associated with prosthesis wear, together with glove staining. Overall, current wearers were satisfied with their devices, while past wearers were dissatisfied. This difference in overall prosthesis satisfaction between current and past wearers was statistically significant ($p < 0.001$, Mann-Whitney U Test). There was no difference in prosthesis satisfaction between prosthesis wearers affiliated with different healthcare centres (i.e., Bloorview Kids Rehab, Sint Maartenskliniek, and Shriners Hospital for Children [Los Angeles]), nor between wearers recruited from healthcare centres versus community-based support groups.

Table V. Challenging activities reported by survey participants.

Activity	Detailed description	Frequency
Household chores	Repairs and household maintenance (i.e., car repairs, shoveling snow, gardening, electrical work); general housework (i.e., vacuuming, dishes, cleaning); use of tools (i.e., hammer, power tools, shovels); heavy lifting; climbing (i.e., ladders)	40%
Sports	Cycling; swinging sports (i.e., golf, baseball, tennis); monkey bars/climbing; swimming; exercising; rock climbing; boating (i.e., canoeing, kayaking); ball sports (i.e., basketball, volleyball)	30%
Hobbies	Playing a musical instrument (i.e., guitar, piano); motorbike and airplane control; woodworking and crafts	22%
Activities of daily living	Food preparation and eating (cutting food, peeling, slicing); dressing (i.e., zippers, buttons, laces, pantyhose, ties); hair styling; typing; washing/personal hygiene; childcare; driving	19%
Social activities	Intimacy (i.e., sex, hugging); clapping; shaking hands; passing through airport security; dancing	8%
Occupational activities	Operating heavy machinery and large vehicles (i.e., farming equipment, trucks); training to be a doctor, surgeon, chemist etc.; law enforcement	6%

Table VI. List of design considerations presented in the questionnaire.

Overall comfort	Overall appearance	Cost
Weight	Colour	Cost of maintenance and repairs
Fit (i.e., comfort of sleeves and/or sockets)	Shape	Cost of prosthesis
Heat/perspiration	Size	
Comfort of harness/straps	Life-like	
How easy it is to put on and take off	Appearance under clothing	
	How you think other people view your prosthesis	
Overall function	**Overall ease of control**	**Overall reliability**
Ability to stabilize objects	Control of opening and/or closing	Frequency of refitting
Ability to make small, precise movements	Frequency of unplanned movements	Durability of harness/straps
Grasp of heavy objects (i.e., grip strength)	Ability to keep objects from slipping from grasp	Durability of control wires/cables
Grasp of big objects	Learning/training needed to use	Glove staining/discoloration
Grasp of small objects	Attention/concentration needed to use	Glove tearing
Grasp of awkward shapes	Physical effort needed to use	Reliability of battery
Grasp of soft objects	Sensory feedback	Frequency of battery charging
Wrist movement/control	Ability to coordinate motions of multiple joints	Frequency of other minor repairs
Speed of opening and closing		Frequency of other major repairs
Noise		Ease of cleaning
Usefulness		Resistance to moisture, sand or dirt

Design priorities for future development

Respondents were asked to list their five highest design priorities in order of importance. Respondents were given the list of attributes presented in Table VI as a guide, but were free to respond with items not on this list. The overall priority score (P_d) ranges between 0 (not important) and 100 (considered most important by all consumers) as calculated by Equation 1. A few additional design priorities that were mentioned by consumers and were not on the list presented in Table VI included: independently moving fingers ($P_d = 9$) by users of electric hands, and elbow and/or shoulder control by consumers with higher level limb absence.

Table VIII and IX present the top ten design priorities of pediatric and adult consumers for passive hands, body-powered hooks and electric hands. The following will discuss these design priorities in detail with supporting evidence garnered from qualitative descriptive data. Subject references codes are included in parentheses.

Table VII. Areas of consumer dissatisfaction (*) or neutral satisfaction.

Design considerations	Passive hand ($n = 39$)	Body-powered hook ($n = 51$)	Electric hand ($n = 81$)
Appearance	–	Life-like Appearance under clothing How other people view your prosthesis	–
Comfort	Heat/perspiration	Heat/perspiration* Comfort of harness*	Heat/perspiration* Comfort of harness Weight
Function	Overall function	Grip strength* Grasp of big objects* Grasp of soft objects* Dexterity Grasp of awkward shapes Wrist movement/control	Noise Grasp of big objects Grasp of soft objects Dexterity Grasp of awkward shapes Wrist movement/control
Control	Sensory feedback	Sensory feedback* Frequency of unplanned movements Ability to keep objects from slipping Coordination of multiple joints Physical effort needed to use	Sensory feedback Frequency of unplanned movements Ability to keep objects from slipping Coordination of multiple joints
Maintenance	Glove staining Ease of cleaning	Frequency of minor repairs Resistance to moisture/sand/dirt	Glove staining* Glove tearing Ease of cleaning Resistance to moisture/sand/dirt
Cost	Cost of prosthesis Cost of repairs	Cost of prosthesis Cost of repairs	Cost of prosthesis Cost of repairs

Table VIII. Pediatric consumer design priorities. All items listed were desired by at least 10% of the population.

Passive hand ($n = 11$)	P_d	Electric hand ($n = 25$)	P_d	Body-powered hook ($n = 9$)	P_d
1. Life-like	35	1. Weight	70	1. Weight	36
2. Fine Motor/dexterity	29	2. Heat	28	2. Overall appearance	29
3. Ease of cleaning	24	3. Glove durability	23	Overall comfort	29
Colour	24	4. Sensory feedback	21	Overall function	29
4. Heat	16	5. Noise	14	3. Size	18
5. Size	15	6. Cost	13	4. Reliability	13
Appearance under clothing	15	7. Life-like	12	5. Life-like	11
Weight	15	8. Wrist movement/control	9	Fit	11
Glove durability	15	9. Size	8	Usefulness	11
6. Sensory feedback	9	Ease of cleaning	8	Harness comfort	11
Resistance to moisture/sand/dirt	9	10. Donning/doffing	7	Ease of control	11
Cost	9			6. Heat	9
	9			Grip strength	9

Note: Design priorities as listed above were desired by at least 10% of the population.

Table IX. Adult consumer design priorities. All items listed were desired by at least 10% of the population.

Passive hand ($n = 23$)	P_d	Electric hand ($n = 48$)	P_d	Body-powered hook ($n = 37$)	P_d
1. Weight	35	1. Weight	45	1. Comfort of harness/straps	29
2. Fit	31	2. Glove durability	23	2. Weight	23
3. Life-like	28	3. Cost	20	3. Cost	20
4. Heat	17	4. Sensory feedback	16	4. Wrist movement/control	20
5. Cost	16	Fine motor skills/dexterity	16	5. Grip strength	18
6. Colour	15	5. Heat	15	Fit	18
Appearance under clothing	15	6. Frequency of unplanned	14	6. Reliability	16
Glove durability	15	movements	12	7. Heat	12
7. Control of opening/closing	12	7. Life-like	10	8. Sensory feedback	9
		8. Comfort of harness	9	9. Ability to maneuver in awkward	8
		9. Reliability	9	positions	8
		Size	9	10. Donning/doffing	
		Independently moving fingers	7	Physical effort needed to use	
		10. Fit	7		
		Wrist movement/control			

Electric prostheses

Weight is a leading design priority for all consumers, and particularly for users of electric devices. A desire for 'a prosthesis with better weight distribution throughout the whole of the limb' (426) is evident. Pediatric users of electric hands desire improvements in wear temperature, as do adults. As one mother reflected:

> The only problem is that my sons says it is too hot and that he feels like someone is roasting marshmallows on his hand. (206)

Other top priority items for pediatric electric users include noise reduction, and ease of donning/doffing.

> An absolutely ridiculous procedure must be endured to get the myo on and off with a 'pull-in sock', a.k.a. a pantyhose that rips; the level of frustration/time taken is so high getting it on, that my daughter often refuses to continue. (234)

Priorities for adult electric users focus more on functional items such as increased dexterity and reduced frequency of unplanned movements. Important to both are improvements in sensory feedback, glove durability, resistance to moisture/dirt, cost, life-like function and appearance, and wrist control. For individuals with high-level limb loss, particularly those with acquired limb absence, better shoulder and elbow control is also paramount:

> Without shoulder reach function, the prosthesis is more hindrance than help. (119)

Improved control and movement of joints (i.e., independently moving fingers, wrist, elbow, and shoulder) was generally desired by users of active devices.

Body-powered prostheses

For consumers of body-powered hooks, reductions in weight are also desired, along with increased harness/strap comfort and temperature/perspiration control. Harness comfort in particular is repeatedly censured both by current and past wearers:

> I love the body-powered system. However, I'm completely exhausted and in a lot of pain after a few hours. I attribute that specifically to the harness system. (475)

The harness system was often cited as the cause of skin irritation and upper body pain leading to discomfort and disuse of the prosthesis:

> Long use means sores the following day and there is no place for the perspiration to go, making the situation worse. (156)

Elimination of the harness altogether, use of softer materials, and greater choice in harnessing configurations are greatly desired by consumers.

Improvements in fit and mechanical reliability are also high-priority items. Reports of pediatric design priorities indicate a greater emphasis on life-like appearance, while adult priorities focus on functional features such as wrist control/movement, overall maneuverability and coordination, together with both tactile and proprioceptive sensory feedback:

> Some way to keep tabs on where it is. I think it is up until it scratches the paint on my car. (114)

More levels and control of grip force are also greatly desired by users of body-powered devices.

Passive/cosmetic prostheses

The greatest difference between pediatric and adult consumer priorities was observed for wearers of passive hands. As evident in Table IX, fine motor control is high on the list of design priorities for pediatric users, perhaps owing to the fact that a passive device is often employed only as a stepping stone to an active prosthesis for young children. Reduced size, ability to clean, resistance to harsh environments (i.e., moisture/sand/dirt), and inclusion of sensory feedback are desired by passive pediatric users and their parents.

In contrast, improvements in fit, cost, glove durability, and reduced weight, are more important to adult users. All wearers of passive devices desire enhancements in lifelike appearance, including better colour, shape and size matching, and less conspicuous appearance under clothing (i.e., streamlined devices and less bulky sockets and harnessing). More effective ventilation for temperature/perspiration control is also a high priority item for passive prosthesis users.

Overall, satisfaction with recent developments in life-like, silicone gloving appeared to be high:

> I have a silicone prosthesis that is difficult to distinguish from my natural hand. To me this is very important. (702)

However, qualitative reports indicate that this technology is not financially accessible to all, and frequent replacements are needed due to poor glove durability and staining.

Overall consumer design priorities

A mutual desire for decreased prosthesis and maintenance costs was apparent. Although for some, prostheses were well funded, many, particularly in the United States, cited difficulties associated with costs:

> The overall cost of the prosthesis needs to be lower. Most 'insurances' pay 80%, but the other 20% is brutal. (495)

> Insurance paid for the initial prosthesis, but the deductible is so high that I can't afford replacement or repairs, so I need to be really careful with this one. (602)

When asked if there were additional 'gadget' features that would be desirable if provided at a reasonable cost and weight, 40% indicated that there would not be, while 60% expressed interest in the idea. The most popular prosthesis accessories that were desired included MP3 players, watches, cell phones, a flashlight, a charge indicator for the battery, or specialty tools. Despite interest in features for added convenience and appeal, the desire for tangible improvements in function, comfort and appearance remains paramount.

Visions for the future

Interest in a number of areas of novel research was evident in the qualitative comments of consumers. In particular, the idea of enhanced, continuous control through nerve and brain interfaces was fairly popular:

> I would like it to be connected to my brain, where it moves when I think about it moving. (112)

Interest in advanced materials for lighter, more durable terminal devices is also appealing to consumers, specifically 'non-conductive polymers', 'carbon fibre', and 'titanium'. The development and application of advanced battery technologies that are light-weight and compact is also desired to reduce weight and size.

Generally, prosthesis rejecters voiced an overall negative view on the usefulness of prostheses and the current state of technology:

> There is nothing that I can't do without them that I want to do – why put up with an expensive, uncomfortable gadget that aids me in no way and takes away many functions, the most important being the ability to 'feel' the world like everyone else?! (83)

> I was hoping that the prosthetic devices would be more advanced than they are at present as in the 30+ years since my amputation I haven't seen great improvements in arms, unlike legs that seem to be greatly improved. (509)

With 68% of non-users willing to reconsider prosthesis use if improvements in the technology were made at a reasonable cost, efforts to address consumer design priorities are critical. It is important to note that disappointment with technology does not preclude appreciation for the overall usefulness of prosthetic devices for many who do find them helpful in their everyday life:

> I feel truly blessed with what I've been able to do with my prosthesis and the fact that it has enabled me to do everything that I've set out to do. (109)

> I did everything possible with my myoelectric; that arm was like my best friend . . . and I still do. I'm just glad that I'm able to have one and of course my passive arm so I can look chic. (182)

Succinctly expressed, the vision of many consumers for the future prosthetic design is as follows:

> My ideal hand is streamlined, lightweight, life-like, functional, and doesn't cost an 'arm and a leg'. (559)

Discussion

Key findings

In agreement with previous studies, comfort-related design issues such as improved heat dissipation [13,15,17], fit, and most definitively, reduced weight [20,30], are paramount on consumers' wish lists for all genres of prostheses. In comparison with a study by Atkins et al. [6], the design priorities for body-powered prostheses as presented in this study remain disturbingly similar to those of consumers over a decade earlier. Harness/strap comfort emerged as a particular concern consistent with previous studies [6,13,23,25,31]. Reductions in weight and cost, and improvements in durability, functional grip and wrist control/movement are also long awaited developments desired by consumers of body-powered devices. These findings indicate the need for continued, intensified exploration of light-weight materials, alternative socket designs or techniques (i.e., osseointegration), novel harnessing configurations, and functional developments that enable wrist rotation/supination/pronation. Demand for low-cost, durable prosthetic solutions may also lead to the development of more suitable devices for developing nations where these design concerns are paramount [23,25,26].

A demand for a more natural, life-like appearance is evident, especially for those using passive or electric hands. Cosmetic silicone gloving has met with consumer satisfaction in this area, however the cost of this technology must be reduced in order for it to become more widely available. Glove durability remains a concern, particularly with regards to staining and discoloration. In terms of functional improvements, both passive and electric users desire increased dexterity and fine motor skills. In comparison with the Atkins consumer study [6], it appears that advancements in battery technology and reliability of the hand and electrodes may have satiated consumer needs in these areas. In contrast, gloving material and a desire for greater finger and wrist movement, remain persistent consumer priorities in this, as in the Atkins study, validating continued development of multi-functional hand prostheses [32–34] and control strategies [35,36].

Overall, greater sensory feedback was of interest for all prosthesis users, and particularly for those using active devices, justifying ongoing research in this area [37–41]. Cost, although ranked by the vast majority as the least important design consideration, nevertheless emerges as an area where improvements are desired, particularly for those whose insurance or medical coverage is limited.

Study limitations

At this point, a brief note on the validity of internet-based surveys is warranted. A number of web-based surveys have been conducted in the past with regards to healthcare on a large scale (i.e., >100 participants) [42–44], and prosthetics on a smaller scale (i.e., <100 participants) [45,46]. Internal consistency and test-retest reliability between a large variety of questionnaires administered via the internet and by other means (i.e., telephone, mail etc.) have been demonstrated [44,47]. With some exceptions [44], response rates are generally lower for emailed surveys than for conventional methods [29]. However, the internet enables more widespread distribution and is less economically taxing and labour intensive, with additional benefits in terms of data quality and questionnaire flexibility/customization [29]. In this study, we employed a number of protocols to minimize sampling limitations including IP address tracking, data consistency analyses, and promotion through local collaborators. It is important to note that the sample population was self-selected, as is often the case in consumer-based surveys, making it difficult to assess the extent to which the opinions expressed are reflective of the population as a whole.

Sampling bias is a potential limitation of internet surveys. It is possible that internet-based surveys may exclude low income individuals [48], and hence concerns regarding high costs of prostheses are actually underestimated in this study. However, as of 2005, 68% of adult Canadians had access to the internet for personal usage [48], while in 2003, 60% of adult in the USA reported internet access [49]. To quantify possible sampling biases, we compared the demographic distribution of this study's electronic respondents from the United States ($n = 92$) to that of a large-scale epidemiologic study ($n = 2477$), also conducted in the United States in 1996 [6]. No statistically significant differences with respect to age, prevalence of trans-radial limb absence, or origin of limb absence was observed. Further, the prevalence of electric hands and body-powered hooks was not statistically different. In this study, 51% of participants were male, as compared to 63% in the Atkins el al. study ($p = 0.02$). However, previous research has found no association between gender and internet access [50].

Conclusions

An improvements in comfort, particularly prosthesis weight, is considered of high priority for individuals of all ages and wearers of all types of prostheses. Design priorities reflect consumer goals for prosthesis use: wearers of passive/cosmetic hands desire a more life-like appearance, while those wearing body-powered hooks desire functional enhancements, and individuals wearing electric hands desire a mixture of both. Tracking user satisfaction is vitally important to providing consumer-centered prostheses.

Acknowledgements

The authors would like to sincerely thank the following for their feedback in the survey development: Hanna Heger, Dr Peter Kyberd, Dr Dick Plettenberg, Dr Virginia Wright, Rafael Reyes, John Krenzel, Julie Shaperman, Sheila Hubbard, Dr Monique Gignac, Dr Colin Macarthur, Randall Alley, Karen Tam, and Nora Fayed. For verifying survey translations, we thank: Jorge Torres, Jorge Silva, Gilles Marconnet, Margriet Poelma, Dr Dick Plettenberg, and Vera van Heijningen. For their promotion of the survey, we thank: Margriet Poelma, Joanne Shida, Shawn Swanson, Karen Lundquist, Lisa Artero, Vera van Heijningen, Tim Pauley, Dr Michael Devlin, Karen Litman, Karen Roberts, Fiona Carnegie, Rosemary Franklin, John Billock, the Prosthetics and Orthotics Care Company, Design Prosthetic Appliance Company, Custom Prosthetic Services Ltd., and Atlantic Prosthetics Inc. We also extend our gratitude to Dan Sorkin, Joyce Baughn, Wayne Renardson, Eric Westover, Brian Wade, and Lorraine Peacock for their recruitment of participants from community-based support groups. Thanks to Toshiba for their endorsement. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, and the Canada Research Chairs Program.

References

1. Draper M, Cohen P, Buchan H. Seeking consumer views in: What use are results of hospital patient satisfaction surveys? Int J Qual Health Care 2001;13:463–468.
2. Crow R, Gage H, Hampson S, Hart J, Kimber A, Storey L, et al. The measurement of satisfaction with healthcare: Implications for practice from a systematic review of the literature. Health Tech Assess [serial online] 2002;6(32). Available: 26 March 2007.
3. Judge S. Family-centered assistive technology assessment and intervention practices for early intervention. Infants Young Children 2002;15:60–68.
4. Mulholland SJ, Packer TL, Laschinger SJ, Lysack JT, Wyss UP, Balaram S. Evaluating a new mobility device: Feedback from women with disabilities in India. Disabil Rehab 2000;22:111–122.
5. Kyberd P, Davey J, Morrison J. A survey of upper limb prosthesis users in Oxfordshire. J Prosthet Orthot [serial online] 1998;10(4). Accessed 5 November 2005 from the website: http://www.oandp.org/jpo/library/1998_04_085.asp
6. Atkins D, Heard D, Donovan W. Epidemiologic overview of individuals with upper-limb loss and their reported research priorities. J Prosthet Orthot 1996;9:2–11.
7. Datta D, Selvarajah K, Davey N. Functional outcome of patients with proximal upper limb deficiency – acquired and congenital. Clin Rehabil 2004;18:172–177.
8. Davidson J. A survey of the satisfaction of upper limb amputees with their prostheses, their lifestyles, and their abilities. J Hand Ther 2002;15:62–70.
9. Fraser CM. An evaluation of the use made of cosmetic and functional prostheses by unilateral upper limb amputees. Prosthet Orthot Int 1998;22:216–223.
10. Gaine WJ, Smart C, Bransby-Zachary M. Upper limb traumatic amputees. Review of prosthetic use. J Hand Surg (Br) 1997;22:73–76.
11. Heger H, Millstein S, Hunter GA. Electrically powered prostheses for the adult with an upper limb amputation. J Bone Joint Surg (Br) 1985;67:278–281.
12. Silcox DH 3rd, Rooks MD, Vogel RR, Fleming LL. Myoelectric prostheses. A long-term follow-up and a study of the use of alternate prostheses. J Bone Joint Surg (Am) 1993;75:1781–1789.
13. Kejlaa GH. Consumer concerns and the functional value of prostheses to upper limb amputees. Prosthet Orthot Int 1993;17:157–163.
14. Pons JL, Ceres R, Rocon E, Reynaerts D, Saro B, Levin S, et al. Objectives and technological approach to the development of the multifunctional MANUS upper limb prosthesis. Robotica 2005;23:301–310.
15. Routhier F, Vincent C, Morissette MJ, Desaulniers L. Clinical results of an investigation of paediatric upper limb myoelectric prosthesis fitting at the Quebec Rehabilitation Institute. Prosthet Orthot Int 2001;25:119–131.
16. Crandall RC, Tomhave W. Pediatric unilateral below-elbow amputees: Retrospective analysis of 34 patients given multiple prosthetic options. J Pediatr Orthop 2002;22:380–383.
17. Ballance R, Wilson BN, Harder JA. Factors affecting myoelectric prosthetic use and wearing patterns in the juvenile unilateral below-elbow amputee. Can J Occup Ther 1989; 56:132–137.
18. Berke GM, Nielsen CC. Establishing parameters affecting the use of myoelectric prostheses in children: A preliminary investigation. J Prosthet Orthot [serial online] 1991;3(4). Accessed 5 November 2005 from the website: http://www.oandp.org/jpo/library/1991_04_162.asp
19. Glynn MK, Galway HR, Hunter G, Sauter WF. Management of the upper-limb-deficient child with a powered prosthetic device. Clin Orthop Relat Res 1986;209:202–205.
20. Hubbard S, Kurtz I, Heim W, Montgomery G. Powered prosthetic intervention. In: Herring J, Birch J, editors. The limb deficient child. Rosemont, Illinois: American Academy of Orthopardic Surgeons; 1997. pp 417–431.
21. Kruger LM, Fishman S. Myoelectric and body-powered prostheses. J Pediatr Orthop 1993;13:68–75.
22. Postema K, van der Donk V, van Limbeek J, Rijken RA, Poelma MJ. Prosthesis rejection in children with a unilateral congenital arm defect. Clin Rehabil 1999;13:243–249.
23. Bhaskaranand K, Bhat AK, Acharya KN. Prosthetic rehabilitation in traumatic upper limb amputees (an Indian perspective). Arch Orthop Trauma Surg 2003;123:363–366.
24. Burger H, Marincek C. Upper limb prosthetic use in Slovenia. Prosthet Orthot Int 1994;18:25–33.
25. Dudkiewicz I, Gabrielov R, Seiv-Ner I, Zelig G, Heim M. Evaluation of prosthetic usage in upper limb amputees. Disabil Rehabil 2004;26:60–63.
26. Fernandez-Palazzi F, de Gutierrez DP, Paladino R. The care of the limb deficient child in Venezuela. Prosthet Orthot Int 1991;15:156–159.
27. Biddiss E, Chau T. Upper extremity prosthesis use and abandonment: A survey of the last 25 years. Prosthet Orthot Int (in press).

28. Lake C, Miguelez J. Comparative analysis of microprocessors in upper limb prosthetics. J Prosthet Orthot [serial online] 2003;15(2). Accessed 5 November 2005 from the website: http://www.oandp.org/jop/library/2003_02_048.asp
29. Hartford K, Carey R, Mendonca J. Sampling bias in an international internet survey of diversion programs in the criminal justice system. Eval Health Prof 2007;30:35 – 46.
30. Datta D, Kingston J, Ronald J. Myoelectric prostheses for below-elbow amputees: The Trent experience. Int Disabil Stud 1989;11:167 – 170.
31. van Lunteren A, van Lunteren-Gerritsen GH, Stassen HG, Zuithoff MJ. A field evaluation of arm prostheses for unilateral amputees. Prosthet Orthot Int 1983;7:141 – 151.
32. Carrozza MC, Suppo C, Sebastiani F, Massa B, Vecchi F, Lazzarini R, et al. The SPRING Hand: Development of a self-adaptive prosthesis for restoring natural grasping. Autonomous Robots 2004;16:125 – 141.
33. Kyberd PJ, Light C, Chappell PH, Nightingale JM, Whatley D, Evans M. The design of anthropomorphic prosthetic hands: A study of the Southampton Hand. Robotica 2001;19:593 – 600.
34. Pylatiuk C, Schulz S, Kargov A, Bretthauer G. Two multi-articulated hydraulic hand prostheses. Artificial Organs 2004; 28:980 – 986.
35. Ajiboye AB, Weir RF. A heuristic fuzzy logic approach to EMG pattern recognition for multifunctional prosthesis control. IEEE Trans Neur Sys Rehabil Eng 2005;13:280 – 291.
36. Huang YH, Englehart KB, Hudgins B, Chan ADC. A Gaussian mixture model based classification scheme for myoelectric control of powered upper limb prostheses. IEEE Trans Biomed Eng 2005;52:1801 – 1811.
37. Carpaneto J, Micera S, Zaccone F, Vecchi F, Dario P. A sensorized thumb for force closed-loop control of hand neuroprostheses. IEEE Trans Neural Syst Rehabil Eng 2003;11:346 – 353.
38. Cranny A, Cotton DPJ, Chappell PH, Beeby SP, White NM. Thick-film force and slip sensors for a prosthetic hand. Sens Actuators A 2005;123:162 – 171.
39. Riso RR. Strategies for providing upper extremity amputees with tactile and hand position feedback-moving closer to the bionic arm. Technol Health Care 1999;7:401 – 409.
40. Zecca M, Cappiello G, Sebastiani F, Roccella S, Vecchi F, Carrozza MC, et al. Experimental analysis of the proprioceptive and exteroceptive sensors of an underactuated prosthetic hand. Lect Notes Contr Inf 2004;306:233 – 242.
41. Dhillon GS, Horch KW. Direct neural sensory feedback and control of a prosthetic arm. IEEE Trans Neural Syst Rehabil Eng 2005;13:468 – 472.
42. Ayantunde AA, Welch NT, Parsons SL. A survey of patient satisfaction and use of the internet for health information. Int J Clin Pract 2007;61:458 – 462.
43. Legters K, Barber Verbus N, Kitchen S, Tomecsko J, Urban N. Fear of falling, balance confidence and health-related quality of life in individuals with postpolio syndrome. Physio Theory Pract 2006;22:127 – 135.
44. Ritter P, Lorig K, Laurent D, Matthew K. Internet versus mailed questionnaires: A randomized comparison. J Med Internet Res 2004;6:e29.
45. Murray CD, Fox J. Body image and prosthesis satisfaction in the lower limb amputee. Disabil Rehabil 2002;24:925 – 931.
46. Murray CD. The social meanings of prosthesis use. J Health Psych 2005;10:425 – 441.
47. Graham AL, Papandonatos GD, Bock BC, Cobb NK, Baskin-Sommers A, Niaura R, et al. Internet- vs. telephone-administered questionnaires in a randomized trial of smoking cessation. Nicotine Tob Res 2006;8:S49 – 57.
48. Canadian Internet Use Survey [Internet]. Statistics Canada; Available from the website: http://www.statcan.ca/Daily/English/060815/d060815b.htm
49. Computer and Internet Use in the United States: 2003 [Internet]. US Census Bureau; Available from the website: http://www.census.gov/prod/2005pubs/p23-208.pdf
50. Ono H, Zavodny M. Gender and the internet. Soc Sci Quart 2003;84:111 – 121.