

## RESEARCH ARTICLE

# An Integrated Approach to Detecting Communicative Intent Amid Hyperkinetic Movements in Children

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### Abstract

Children with hyperkinetic movement (HKM) often have limited access to traditional augmentative and alternative communication technologies (e.g., mechanical switches). To seek a communication solution for these children, this study explored the possibility that discernable biomechanical patterns, related to preference, exist amid HKM. We deployed a unified approach to analyse a child's movements, fusing caregiver and clinician observations with quantitative data (accelerations of the upper extremities). Two case studies were examined. In both, the accelerometer data identified preference at adjusted accuracies statistically above chance using a linear discriminant classifier. Visually, communicative movement patterns were identified in the first child ( $\kappa=0.25-0.27$ ) but not in the second child ( $\kappa=0.03-0.11$ ). Implications of this study include possible enhancement in communication and independence for these children.

**Keywords:** *Communication; Accelerometer; Observational analysis; Hyperkinetic movement; Paediatric*

### Introduction

Hyperkinetic movement (HKM) is an excess of uncontrolled movement. In the paediatric population, HKM is typically the result of an injury to or abnormal function of the basal ganglia, cerebellum, or cerebral cortex, most frequently associated with dyskinetic cerebral palsy (DCP) (Fahn & Jankovic, 2007; Lebedowska, Gaebler-Spira, Burns, & Fisk, 2004). DCP affects 0.15 to 0.25 per 1000 children in Western countries (Sanger, 2006) and is a sub-classification of cerebral palsy (CP), in which motor impairments are secondary to anomalies or lesions in the brain during early development (Mutch, Alberman, Hagberg, Kodama, & Perat, 1992). These motor impairments are reflected in the majority of children with DCP as significant impairments in gross and fine motor skills. Himmelmann, Hagberg, Wiklund, Eek, & Uvebrant, (2007) found that 79% (38/48) of their sample of children with DCP were classified as a level IV or V on the Gross Motor Function Classification System (GMFCS), suggesting limitations in self-mobility while 77% (37/48) were classified as a level IV or V on the Bimanual Fine Motor Function (BFMF), indicating that fine motor skills were at best limited to grasping (Himmelmann, Beckung, Hagberg, & Uvebrant, 2006).

Children with cerebral palsy commonly have a discrepancy between their expressive and receptive language skills. The expressive language skills, or the child's ability to verbally communicate is often hindered, while the child's ability to understand language remains intact (Byrne et al., 2001; Pirila et al., 2007). A recent longitudinal study of children with cerebral palsy found that 85% (11/13) of the children with a GMFCS level IV and 100% (18/18) of those with a GMFCS level V had significantly lower communicative means compared to children with typical development (Voorman, Dallmeijer, Van Eck, Schuengel, & Becher, 2010). Despite the physical and communicative challenges, children with DCP tend to have relatively good cognitive skills (Jan, Lynch, Heaven, & Matsuba, 2001).

This dilemma can be framed in the terminology of the International Classification of Functioning, Disability and Health (ICF): A child's cognitive capability exceeds his or her cognitive performance and this can have a tremendous impact on both the child's and the family's quality of life, specifically with respect to the basic communication of an individual's preference (Craig, Tran, McIsaac, & Boord, 2005; WHO, 2001). One way to narrow this gap is to introduce technology as an environmental facilitator.

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### *Access Technologies for Children with Hyperkinetic Movement*

Despite reports that arm trajectories are more varied in children with DCP compared to children with typical development (Sanger, 2006), automatic gesture recognition may be a potential access technology for children with excessive movement. Roy, Panayi, Erenshiteyn, Foulds, and Fawcus (1994) used drama to elicit gestures in children with cerebral palsy; in this study, four children were able to make 12 to 27 recognizable gestures based on arm position, velocity, and acceleration signal features. Building on these findings, Morrison and McKenna (2002) utilized a computer vision-based gesture recognition system for a child with cerebral palsy with only a 5.6% error rate. Similar studies have been successful at utilizing gesture recognition to track nose, chin, thumb, or foot movement (Betke, Gips, & Fleming, 2002; Glips, Betke, & DiMattia, 2001). Collectively, these studies indicate that, even with increased variability in HKM, children may still be able to produce machine-discernible patterns. However, no studies have directly examined the possibility that HKM may carry useful information relating to an individual's preference.

### *Rationale for an Integrated Approach to Preference Detection Amid HKM*

To address the hypothesis of preference-related content in HKM, a systematic description of movement is required. Movement is routinely quantified through calculating the change in velocity over time, or the acceleration of the movement; this is captured using accelerometers (Shaikh et al., 2008). Movement is also characterized through real-time and retrospective observational techniques. One such technique is Laban Movement Analysis, a descriptive tool that qualitatively assesses movement with respect to four major components: body, effort, shape, and space (Swaminathan et al., 2009; for a complete review of Laban Movement Analysis please refer to Newlove & Dalby, 2004). However, the combination of quantitative and observational analysis is less common, although the idea of "methodological pluralism," or combining multiple methods, is strongly advocated in the communications literature (Petry & Maes, 2006; Reid & Green, 2002). This idea is relevant to the problem of decoding preference via movements, in that quantitative data may enhance the detection of communicative intent, while observational analysis may provide valuable contextual information about the complex nature of HKM and the idiosyncratic mechanisms of communication (Hogg, Reeves, Roberts, & Mudford, 2001).

In addition to multiple methods, multiple informant perspectives may be instrumental in understanding the communicative intent of HKM. The primary caregiver learns to decipher idiosyncratic mechanisms of communication through gradually developed knowledge of subtle gestural or expressive changes (Goode, 1990).

This insight about the client's communicative intent is regarded as indispensable and thus the caregiver often acts as the liaison between clinicians and the individual with profound disabilities (Hemsley, Balandin, & Togher, 2008; Yamasato et al., 2007). On the other hand, clinicians can provide a fresh and unbiased opinion about a client's communication. In fact, Petry & Maes (2006) argue that both caregiver and clinician interpretations should be considered as complementary viewpoints. However, undue stress is placed on the caregiver or clinician who serves as the patient's exclusive translator, and interpretation errors may abound (Happ, Roesch, & Kagan, 2004). Studies have reported that systematic assessment of a patient's preference, for example, by counting "approach responses" (Pace, Ivancic, Edwards, Iwata, & Page, 1985), more accurately reflects a patient's choice than mere clinician belief, furthering the notion that clinician opinion should not be the sole interpretation of patient preference (Green, Gardner, & Reid, 1997; Reid, DiCarlo, Schepis, Hawkins, & Stricklin, 2003).

In light of the above, an integrated approach that embodies multiple methods and perspectives may be a promising strategy for detecting preference in HKM. In particular, in this paper, we propose to systematically analyze a time-varying quantitative measure of upper body movement alongside an observational description of this movement, incorporating viewpoints of both the primary caregiver and clinician.

## **Methods**

### *An Integrated Approach to Decode Preference in HKM*

The integrated approach contains three main components: a communication activity, observational movement analysis, and automatic movement classification. Figure 1 provides an overview of this process and each component is described in more detail in the sections that follow. The top portion of the figure is the communication activity, which provides the context for video and biomechanical data collection. The left half of Figure 1, observational analysis, assesses clinician and caregiver ability to visually discern movements associated with different preferences. The right portion of Figure 1 outlines the automatic movement classification, which gauges the ability to algorithmically discriminate between preferences on the basis of biomechanical time series.

### *Participants*

The proposed method is generally suitable for clients who are non-speaking and have a diagnosis of hyperkinetic movement. To explore the potential relationship between HKM and communication we focus on two participants with HKM. Both participants had an established diagnosis of dyskinetic cerebral palsy; were classified as level IV or V on the Manual Ability Classification System (MACS); had corrected-to-normal vision; and

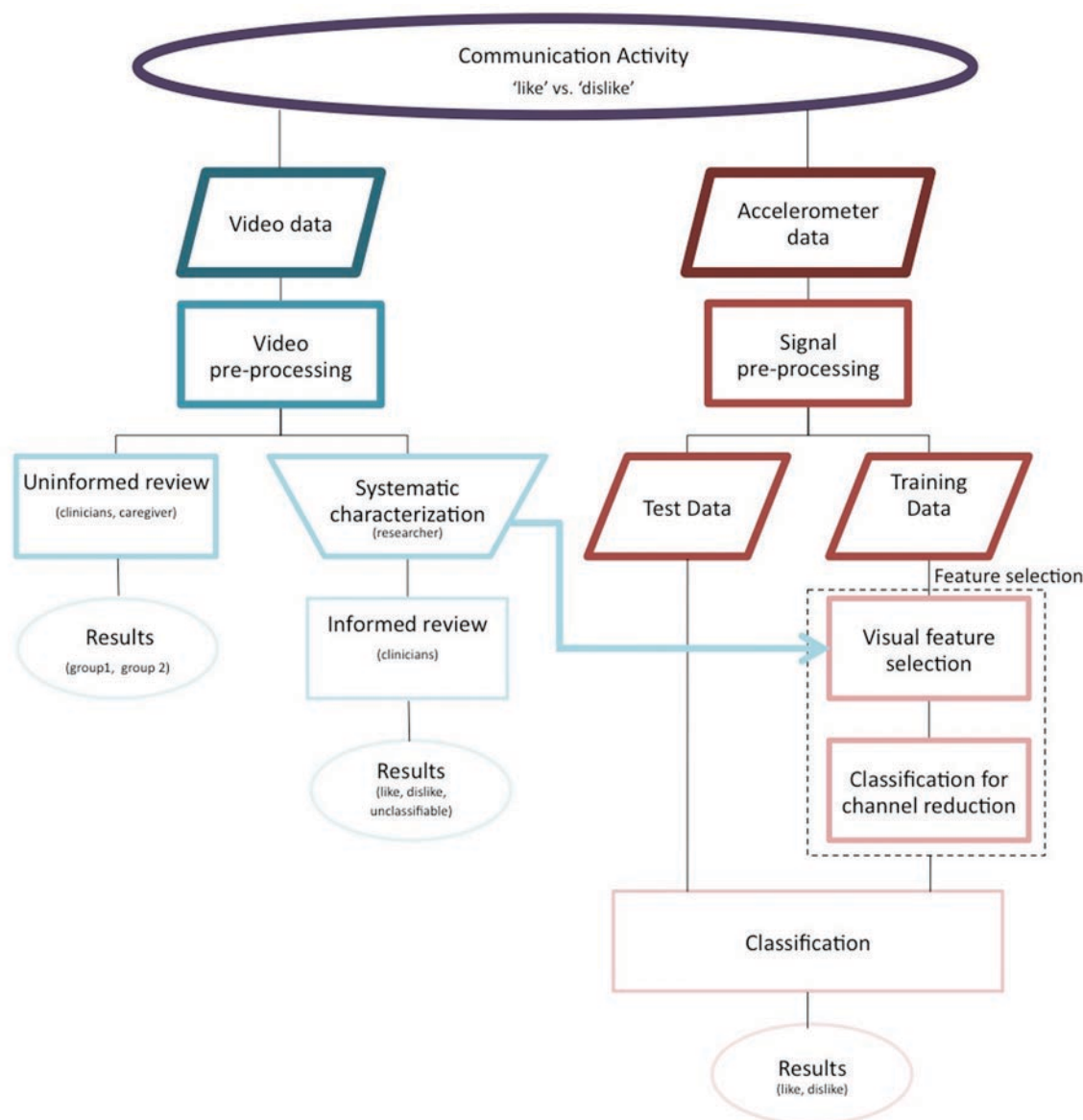


Figure 1. Integrated approach to decoding preference in hyperkinetic movement: left branch depicts visual classification of preference while right branch summarizes the automatic classification of preference.

were able to communicate basic yes/no responses and understand spoken English. Prior to participating in the study, assent was obtained from participants and consent was obtained from the participant's primary caregiver. Ethical approval for this study was obtained from Holland Bloorview Kids Rehabilitation Hospital and the University of Toronto, Canada.

Billy (pseudonym) was a 9-year-old boy with dyskinetic cerebral palsy. Billy was non-ambulatory and was classified as MACS Level V. He had normal auditory and visual status and attended a Grade 4 Individualized Education Plan elementary school program. He communicated through eye gaze and vocalization with a picture communication symbols communication board. The second participant was Steve (pseudonym), a 6-year-old boy with dyskinetic cerebral palsy and MACS Level V. Steve wore corrective lenses and hearing aids bilaterally. He was in Grade 1 in an integrated education and

therapy school. His primary means of communication was vocalization with a familiar caregiver.

#### Instrumentation

In this study, the biomechanical time series were body accelerations, but they can be any time-varying kinematic, kinetic, or spatio-temporal measurement. Tri-axial accelerometers (Freescall, model MMA7260Q<sup>1</sup>) were fastened, using medical-grade adhesive tape, to the manubrium, bilaterally to the mid-shaft of the humerus; bilaterally to the dorsum of the mid-shaft between the ulna and radius; and to the posterior aspect of the head, at the lambda, using an elastic headband. See Figure 2 for a schematic representation of these placements. Acceleration signals were acquired using a data acquisition card (National Instrument USB 6210<sup>2</sup>) and a custom LabVIEW<sup>3</sup> application at



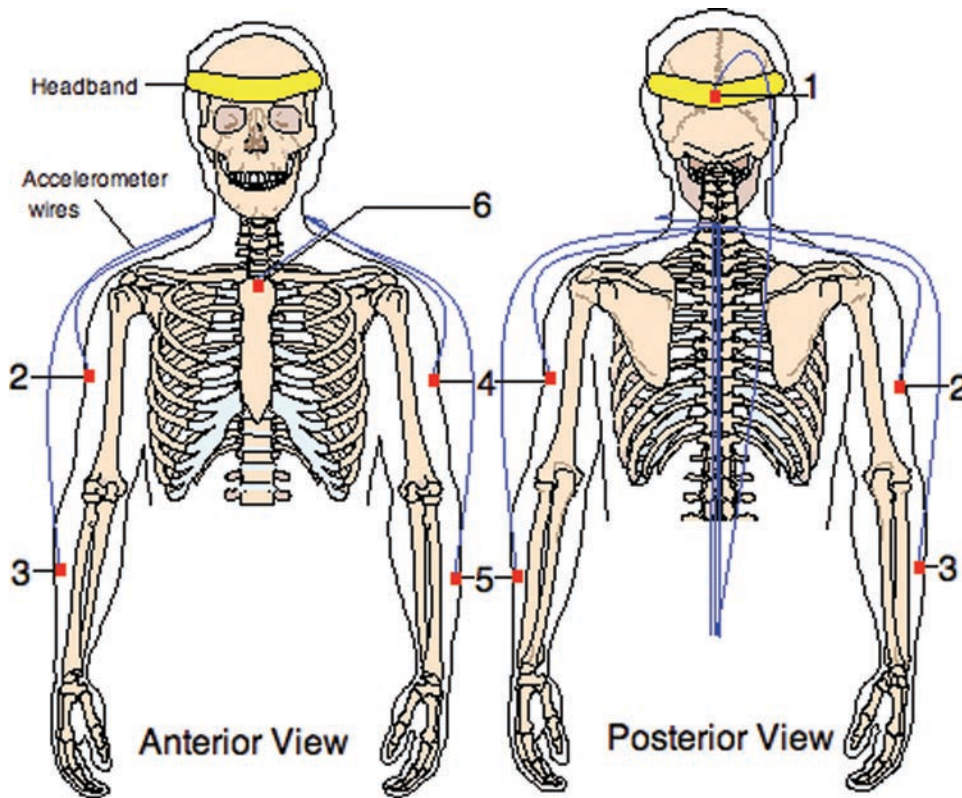


Figure 2. Accelerometer placement: 1. posterior aspect of the head 2. right upper arm (mid-shaft of the humerus) 3. right forearm (dorsum of the mid-shaft between the ulna and radius) 4. left upper arm (mid-shaft of the humerus), 5. Left forearm (dorsum of the mid-shaft between the ulna and radius) and 6. Manubrium.

a sampling rate of 1kHz, and were stored in a desktop computer.

Concurrent with the collection of accelerometer data, two-dimensional videos were captured, at a recording rate of 30 frames/s, in frontal and sagittal views of the participant. The video also captured an LED light that was controlled by the custom LabVIEW application, which turned it on when accelerometer data collection commenced and turned it off when data collection stopped. The video data were saved on a Sony Handycam camcorder<sup>4</sup> hard drive, and transferred to a secure network where the activation of the LED light was used to synchronize the video and accelerometer data. The overall experimental set-up is summarized in Figure 3.

### Communication Activity

The purpose of the communication activity was to elicit hyperkinetic movement alongside a gestural expression of preference. This was accomplished through the presentation of visual stimuli, on a laptop computer, that the child either liked or did not like. Prior to beginning the activity the laptop was positioned in front of the child and adjusted until the child could see the visual stimulus. The activity was composed of three to four trial blocks. Each block consisted of 10 visual stimuli: 5 images of items the child liked and 5 images of items the child disliked. As the child was unable to provide a reliable, unfacilitated yes/no response for a priori selection of these images, they were selected from an

image pool created by the child's caregiver to increase the likelihood of presenting affective images during the block. Please refer to Table I for a list of these items. If the item given a priori was not in multi-media format then a pictorial representation of the item was used in place of the actual object. The 10 visual stimuli were presented to the child in a randomized order on a laptop computer. The stimulus included a *LIKE* sign in the bottom left corner of the screen and a *DO-NOT-LIKE* sign in the bottom right corner of the screen. When the stimuli appeared the caregiver told the child what the stimuli was (e.g., It's a plane) and then asked the child if he liked the stimuli (e.g., Do you like planes). The child's task was to point to the *LIKE* sign if he liked what the picture represented and at the *DO-NOT-LIKE* sign if he disliked what the picture represented. Although instructed to indicate their preference by pointing, the children did not actually have the motor capability to unambiguously make contact with the *LIKE* and *DISLIKE* targets, leaving no objective evidence that the participants had accomplished the task. Thus, to verify each response, the caregiver queried the child after an apparent attempt to point, and the child responded through his or her usual means of communicating "yes" or "no". Upon verification, the caregiver activated the mechanical switch (shown in Figure 3) corresponding to the child's preference. The time of stimuli presentation and switch activation were automatically recorded on the computer for subsequent data segmentation.

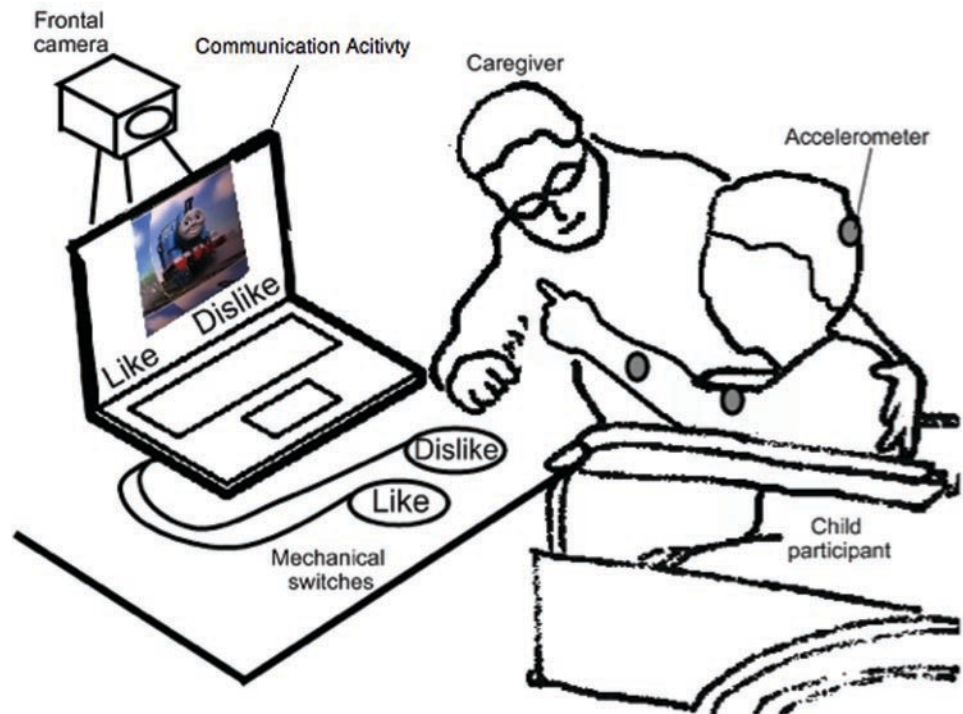


Figure 3. Experimental set-up consisted of the participant partaking in the communication activity while accelerometers and a two-dimensional video camera captured the child's movements. During the communication activity, the caregiver activated the 'like' switch if the child indicated that he/she liked the stimulus and the 'dislike' switch if the child did not like the stimulus. 'Like' responses were followed by a 15 sec video clip, related to the stimuli and then 10 sec of rest; 'dislike' responses directly triggered 10 sec of rest.

Table I. Visual stimuli provided a priori by the caregivers.

Participant	Stimuli	
	"Like"	"Dislike"
Billy	The television show, "America's Funniest Home Videos", Hockey, The Weather Channel, Planes, The television show, "George of the Jungle"	Tornadoes, The television show, "Barney", Carrots, Stuffed animals, The television show, "Dora the Explorer"
Steve	The television show, "Bob the Builder", The television show, "Thomas the Tank Engine", "Lightening McQueen" from the movie, Cars, Fire engines, The television show "Mighty Machines"	The movie, "Horton Hears a Who", Bouncy Castles, "Porky the Pig" from the television show "Looney Tunes", "Mater the Tow Truck" from the movie "Cars"

To engage the child, he or she was rewarded with a 15-s video related to the liked stimulus (e.g., if the stimulus was "Bob the Builder" the video was a clip from the television show "Bob the Builder"). Alternatively, if the child communicated dislike towards the picture, he or she was rewarded by the immediate removal of the stimulus. To account for variability in hyperkinetic movement, data were collected over four 1-hour sessions, each separated by at least one week.

Visual Preference Detection

Movements were visually ascertained through three video analyses: a uninformed review by two occupational therapists (OT<sub>1</sub> and OT<sub>2</sub>) and a familiar caregiver (CG), a systematic characterization of each response, and an informed review by the clinicians (OT<sub>1</sub> and OT<sub>2</sub>). Each of these analyses is explored in greater detail in the sections that follow.

*Pre-processing Video Data.* Prior to analysing the videos, each session was segmented into individual responses based on the caregiver's activation of the response switch. Videos were cropped to include only the child, thus removing background information that could potentially reveal a 'like' or 'dislike' response. To ensure that reviews were based on the movements and not other communication modalities, the video resolution was reduced to mask the participant's eye movement and the audio data were removed. The visibility of movements was not compromised. Processed responses across all sessions were randomized and burned to a CD.

*Uninformed Video Review by Clinicians and Caregiver.* The child's primary caregiver and two occupational therapists, specializing in pediatric movement disorders, completed the uninformed video review. This review evaluated the rater's ability to classify the child's response as either a 'like' or 'dislike', based solely on a visual record

of the child's movement. Each reviewer was given a CD containing the pre-processed data described previously, and was instructed to categorize the responses into two categories, based on the child's arm, trunk, and head movement. The reviewers were not given instructions regarding the type of movements on which to base this categorization, rather they were asked to specify the movement, or combination of movements, they used to categorize the segments. Reviewers were allowed to watch each response multiple times.

*Systematic Characterization of Movement.* A researcher, who was not blinded to the child response, reviewed the video a second time. The purpose of this systematic review of each response was to determine archetypical 'like' and 'dislike' movement patterns. A custom classification scheme that delineated 12 movements of the child's head, trunk, shoulder, and elbow was developed to characterize the movement patterns; a full description of each movement is provided in Table II. The classification scheme was loosely based on the "body" and "effort" components of Laban's Movement analysis; the interested reader is referred to Newlove & Dalby (2004) for a full review. The body classification assessed the presence or absence of a given movement. If the movement was present, the effort classification recorded the type of movement present, namely, the weight, timing, and trajectory of the movement. Table III provides a detailed description of the specific effort movement classes. For every recording session, participant movement was classified using this scheme, thereby producing archetypical 'like' and 'dislike' responses that were subsequently used to inform the video review and the visual feature extraction from acceleration data.

Table II. Summary of the movements of interest used in the "body" portion of the systematic movement classification.

Body part	Movement of interest
Head	Left, Right
Trunk	Anterior, Posterior
Shoulder	Horizontal adduction, Horizontal abduction, Vertical adduction, Vertical abduction
Elbow	Flexion, Extension, Pronation, Supination

Table III. Definition of the movement characteristics explored in the "effort" portion of the systematic movement classification.

Characteristic	Definition	Classifications
Weight	The strength of the movement	Light vs strong
Space	The path the movement follows to its destination	Flexible vs direct
Time	The timing of the movement	Sustained vs sudden

*Informed Video Review by Clinicians.* A final video review utilized the prototypical responses identified previously to inform the clinicians of the specific movement patterns of interest. The clinician's from the uninformed video review re-assessed the videos, indicating when a typical movement or combination of typical movements was present. Three factors were considered in order to minimize the carry-over of knowledge from the first review: (a) the sheer number of responses (over 100), (b) the 1-month separation between reviews, and (c) the different order of presentation of responses in each review. Unlike the first review, responses were categorized in one of three classes: like, dislike, and unclassified. This latter category was introduced because the typical response did not occur in all video segments. The raters were instructed to use the unclassified category if the child's response was neither a prototypical like nor a prototypical dislike. This second video review explored the potential of enhanced expert identification of communicative movements using information from a systematic characterization.

*Video Review Analysis.* A prevalence-adjusted bias-adjusted kappa ( $\kappa$ ) (PABAK) was used (Byrt, Bishop, & Carlin, 1993) to assess the agreement between clinician or caregiver ratings and the actual responses of the child, the inter-rater reliability, and the inter-review reliability (agreement within-clinician between uninformed and informed reviews). For each rater, the latter comparison only considered the responses deemed classifiable in the informed review. Statistical agreement was interpreted according to Kramer & Feinstein, (1981): slight agreement, 0-0.20, fair agreement, 0.21-0.40, moderate agreement, 0.41-0.60, substantial agreement, 0.61-0.80, and excellent agreement, greater than 0.80.

#### Automatic Preference Classification

*Pre-processing.* Data recorded from the accelerometers over one data collection session required pre-processing to remove noise from the signal and to segment it into relevant sections; an overview of the process is provided in Figure 4. The raw accelerometer signals depicted in Figure 4a were converted into physical units ( $m/s^2$ ) via a linear transformation derived from a pre-session static calibration, yielding transformed data depicted in Figure 4b. To separate the signals into sections that represented movement corresponding to 'like' and 'dislike' responses, the transformed data were segmented based on the caregiver's activation of the response switch, depicted in Figure 4c. Finally, noise was removed from the segmented signals by applying a low pass Butterworth filter with a 20 Hz cut off frequency. The results of the pre-processing are depicted in Figure 4d.

*Feature Selection and Classification.* To classify preference using the accelerometer data, a linear discriminant analysis (LDA) classifier was developed based upon salient features extracted from the pre-processed signals. An overview of the feature selection and classification process is provided in Figure 5.



Pre-processed accelerometer signals were not sent directly to the classifier; instead, a feature (e.g., mean, variance) of the signals that differentiated movements corresponding to a ‘like’ response from those corresponding to a ‘dislike’ response was selected and used

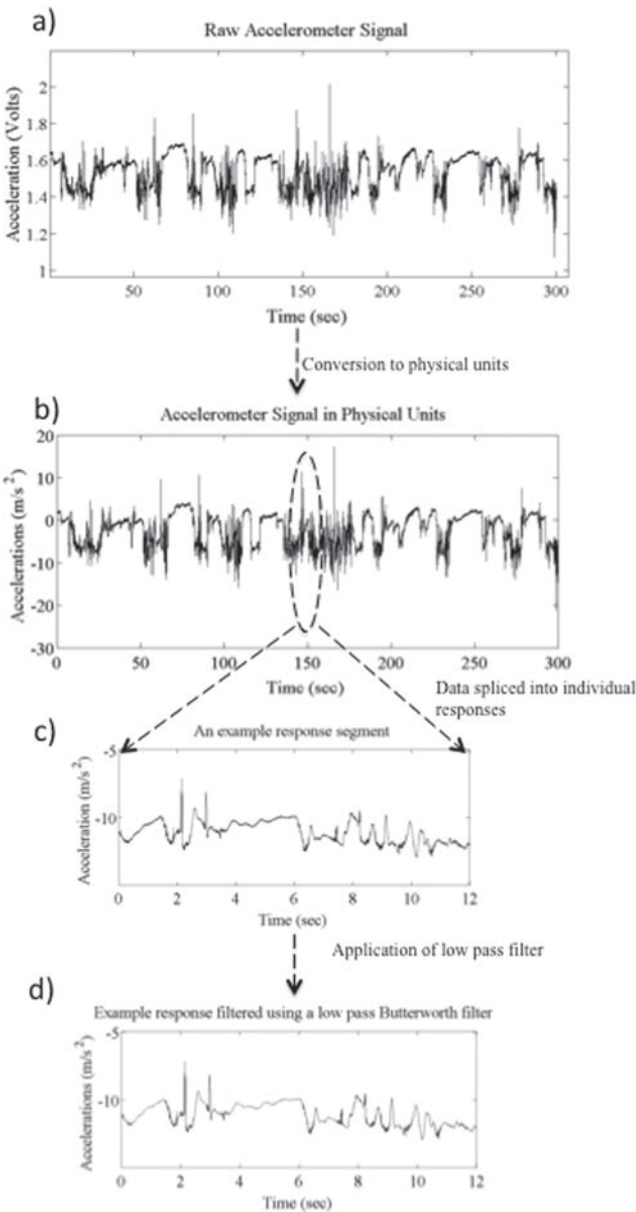


Figure 4. Accelerometer signal pre-processing. a) raw accelerometer signals; b) accelerometer signal converted into physical units (m/s<sup>2</sup>); c) accelerometer signal spliced into individual responses d) individual responses filtered by a low pass Butterworth filter.

for classification. The method of selecting the most discriminatory feature is depicted in Figure 5a. Briefly, specific features of the accelerometer signals were selected as candidate features using a priori knowledge of the physical characteristics of the subject’s ‘like’ and ‘dislike’ response (e.g. if a prototypical ‘like’ contained rapid movements and ‘dislike’ contained slower, more subtle movements, the mean area under the curve of acceleration over time was considered a candidate feature). These features were then visually inspected for class separability using 2-D and 3-D scatter plots and parallel coordinate plots. The most visually discriminatory feature was selected for automatic preference classification.

Once the most discriminatory feature was selected, we next selected the combination of accelerometer channels that would maximize classification accuracy, as depicted in Figure 5b. The purpose of this step was to reduce the large number of classifier inputs (18 potential channels: 6 accelerometers × 3 axes/accelerometer) by selecting the channels that contained the information most relevant to the participant’s intended movement. The data were segmented into training and testing subsets using an 80-20 split. The training data were then randomly divided into five subsamples, and a linear discriminant analysis (LDA) was applied to each subsample to test the class separability between the ‘like’ and ‘dislike’ responses. This was repeated, 10 times, for all possible iterations of 1, 2, and 3 accelerometer channel combinations. For each subsample, sensitivity, specificity, and adjusted accuracy (accounting for the unequal number of responses in each class) were calculated (Nahn & Chau, 2010). The accelerometer channel combination with the highest average adjusted accuracy was then used to classify the test data (Figure 5c). Classifier performance was evaluated using sensitivity, specificity, and adjusted accuracy calculated for 50 iterations of channel selection and classifier evaluation.

Sensitivity =  $\frac{\text{True Likes}}{(\text{True Likes} + \text{False Dislikes})}$  (a)

Specificity =  $\frac{\text{True Dislikes}}{(\text{True Dislikes} + \text{False Likes})}$  (b)

Adjusted Accuracy =  $\frac{\text{Sensitivity} + \text{Specificity}}{2}$  (c)

Table IV. Video review results: table entries are prevalence-adjusted bias-adjusted kappa (κ) values for the validity and inter-rater reliability of the clinicians (OT1 & OT2) and caregiver (CG) in both the informed and uninformed video review.

Review		Validity			Inter-rater reliability		
		OT1	OT2	CG	CG-OT1	CG-OT2	OT1-OT2
Billy	Uninformed	0.20*	0.21*	0.25*	0.08	0.11	0.59**
	Informed	0.27*	0.27*	-	-	-	0.58**
Steve	Uninformed	0.03	0.045	0.11	0.08	0.11	0.02
	Informed	-0.08	-0.08	-	-	-	0.01

Note. \* = strength of the agreement is fair (0.20 < κ < 0.41).  
\*\* = strength of the agreement is moderate (0.40 < κ < 0.61).

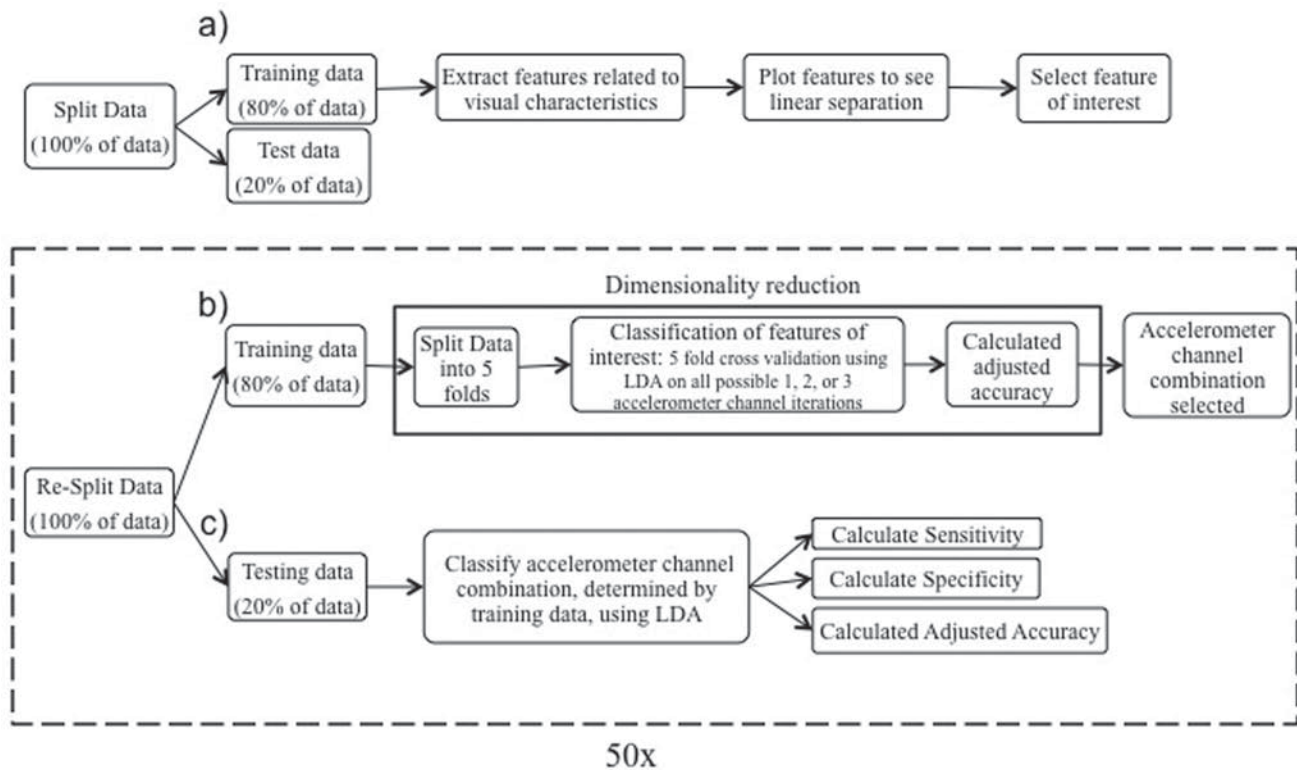


Figure 5. Feature selection and classification. a) Extraction of the feature of interest; b) Dimensionality reduction; c) Test data classification. Step's b) and c) were repeated fifty times yielding estimates of sensitivity, specificity and adjusted accuracy.

Table V. Systematic characterization of movement.

	"Like" Response	"Dislike" Response
Billy	<ul style="list-style-type: none"> <li>Head turned both left and right and right shoulder horizontal abducted &amp; adducted</li> </ul>	<ul style="list-style-type: none"> <li>Head turns to left while shoulder vertical abducted or adducted</li> <li>Right shoulder vertical abduction or adduction with right elbow flexion</li> </ul>
Steve	<ul style="list-style-type: none"> <li>Left elbow flexion or extension in a sudden manner</li> </ul>	<ul style="list-style-type: none"> <li>Sustained left elbow flexion</li> </ul>

*Statistical Analysis of the Automatic Preference Classification.* The distributions of the adjusted accuracy, sensitivity, and specificity vectors were tested for normality using a Lilliefors test (MATLAB Statistics Toolbox<sup>5</sup>). If normal, a single-sided student's t-test was used to test the hypothesis that accuracy, sensitivity and specificity rates were statistically different from chance ( $p < 0.05$ ). Otherwise, a Wilcoxon rank sum test (MATLAB Statistics Toolbox) was employed. Finally, the adjusted accuracies were compared to those of the human expert raters in the informed and uninformed reviews, using a Wilcoxon rank sum test.

## Results

### Case Study 1

Billy's left arm was restrained and he had frequent head movements, during which his chin contacted his trunk. As a consequence, only the right arm and head accelerometers were used. Although the caregiver pre-determined an equal number of like and dislike stimuli, Billy responded positively towards the majority of

stimuli with 107 uncontaminated 'like' responses and only 33 uncontaminated 'dislike' responses.

Table IV summarizes the PABAK, which tested the validity and inter-rater reliability of the video review. In the uninformed video review, the ratings of Billy's caregiver agreed most closely with the true responses. Inter-rater reliability was moderate between the occupational therapists and only slight between any clinician and the caregiver.

As detailed in Table V, the systematic characterization identified specific combinations of head and shoulder movements as prototypical responses. The prototypical 'like' response was found in 71% (76 of 107) of the total 'like' responses and in 1.3% (4 of 33) of the total 'dislike' responses, whereas the prototypical 'dislike' response was found in 66.7% (22 of 33) of the total 'dislike' responses and in 12.3% (13 of 107) of the total 'like' responses.

Once clinicians were armed with descriptions of the prototypical responses, their ratings improved, reaching fair agreement with the true responses. Inter-rater reliability remained moderate. Neither clinician had strong between-review reliability, reaching only slight



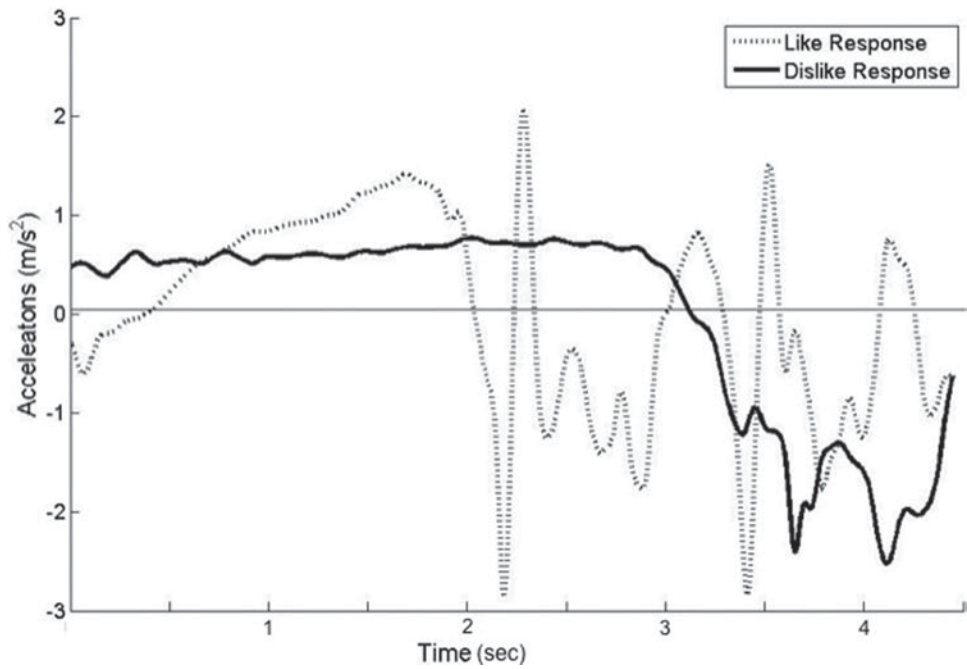


Figure 6. Accelerometer signals of Billy's head movement for a prototypical 'like' and 'dislike' response in the horizontal plane. The feature that differentiated between preferences was the absolute area under the curve.

Table VI. Automatic classification results

	Classifier	Adjusted accuracy (std)	Sensitivity (std)	Specificity (std)
Billy	2-feature Fisher LDA	0.685* (0.11)	0.642* (0.11)	0.728* (0.20)
	3-feature Fisher LDA	0.679* (0.10)	0.635* (0.10)	0.722* (0.19)
Steve	2-feature Fisher LDA	0.612* (0.10)	0.567* (0.15)	0.658* (0.15)
	3-feature Fisher LDA	0.629* (0.10)	0.604* (0.15)	0.655* (0.16)

Note. \* = ( $p < 0.05$ ): rejects  $H_0$ : Adjusted accuracy = 0.5, Sensitivity = 0.5 or Specificity = 0.5

agreement levels ( $\kappa = -0.077$  for  $OT_1$ ,  $-0.023$  for  $OT_2$ ) using a PABAK. In this review,  $OT_1$  categorized 45 responses as 'like', 34 as 'dislike', and 61 as unclassifiable;  $OT_2$  flagged 48 responses as a 'like', 38 as 'dislike', and 54 as unclassifiable.

The systematic video review and the visual analysis of the accelerometer data identified the absolute area under the curve (i.e., the sum of the area between the acceleration curve and zero acceleration without regard for whether the acceleration was in a positive or negative direction) as the feature of interest. Figure 6 displays a prototypical 'like' and a 'dislike' response, exhibiting that the feature of interest differs between these responses. A linear discriminant classifier of up to three features was considered to maintain an appropriate ratio between training sample size ( $n$ ) and feature subset dimensionality ( $d$ ); where  $n/d > 5$  (Nahn & Chau, 2010). The average adjusted accuracy, sensitivity, and specificity rates are summarized in Table VI.

A Lilliefors test revealed positively skewed distributions for all performance measures. Thus, a Wilcoxon rank sum test was used to test the null hypothesis that the average adjusted accuracy, sensitivity and specificity were not different from chance.

The adjusted accuracies reported in Table VI for automatic movement classification exceeded those of the uninformed ( $OT_1$  65.87;  $OT_2$  64.65%; CG 62.22%;

$p < 0.009$ ) and informed ( $OT_1$  66.09%;  $OT_2$  67.65%;  $p < 0.04$ ) video reviews.

### Case Study 2

Steve produced 51 uncontaminated 'like' and 38 uncontaminated 'dislike' responses. Inattention and fatigue contributed to the lower number of responses collected from this participant. Moreover, in some cases, there was a discrepancy between Steve's attempt to communicate and the primary caregiver's interpretation of his intent.

The video results for Steve are also summarized in Table IV. Unlike the first case study, both clinician and caregiver ratings had only slight agreement with Steve's responses in the uninformed review, and the reliability between clinicians was modest when calculating the PABAK. However, similar to the first case study, clinician and caregiver ratings exhibited only slight agreement.

Table V describes the prototypical 'like' and 'dislike' responses for Steve. The typical 'like' response was found in 71% (36/51) of the total 'like' responses and in 32% (12/38) of the total 'dislike' responses. The typical 'dislike' response was found in 49% or 18/38 of the total 'dislike' responses and in 29% (15/51) of the total 'like' responses.

The results of the informed clinician review of Steve's movements are also summarized in Table IV. PABAK calculations found agreement between clini-

cian/caregiver and actual response, inter-rater reliability, and between-review reliability were all low ( $= -0.09$  and  $-0.11$  for  $OT_1$  and  $OT_2$ , respectively). In this review,  $OT_1$  categorized 26 responses as 'like', 23 as 'dislike', and 44 as unclassifiable;  $OT_2$  flagged 29 responses as a 'like', 21 as 'dislike', and 44 as unclassifiable.

Note that the systematic characterization (Table V) identified the time aspect of the Laban effort classification rather than a specific movement as discriminating; 'like' responses were associated with sudden movements while 'dislike' was paired with sustained motion. Thus, the first derivative of acceleration—jerk—was calculated. The absolute area under the jerk curve was explored as the feature of interest. Again, linear discriminant classifiers with up to three features were considered. The average adjusted accuracy, sensitivity, and specificity rates for 10 runs of the 5-fold-cross-validation are summarized in Table VI. A Wilcoxon rank sum revealed that movement classification accuracy by the accelerometer, reported in Table VI, achieved significantly greater adjusted accuracies than both the uninformed (51.40%, 52.38%, and 55.49% for  $OT_1$ ,  $OT_2$ , and CG, respectively); and informed (46.5% and 56.90% for  $OT_1$  and  $OT_2$ , respectively) reviews.

## Discussion

This method must be tested on more children before definitive conclusions can be drawn about its reliability or whether communicative patterns remain amid HKM in children. Nevertheless, the current findings do suggest that, in the two cases studied, detectable patterns exist amid hyperkinetic movement.

### Caregiver Intuition

In the uninformed review, the caregiver's categorization of Billy's movement was more accurate than that of the occupational therapists in terms of agreement with the actual responses. One may have predicted that a familiar caregiver would have an advantage over the clinicians; however, the caregiver's results were particularly impressive because she typically relied on the child's vocalization and eye gaze, both of which were removed from the video. This finding implies that communicative mechanisms, beyond those consciously identified by the caregiver, were employed. This finding is supported by Goode's symbolic interactionist theory, which argued that within a family, unspoken communication is just as important as speech (Goode, 1990). Goode also highlights the superior ability of the familiar caregiver to interpret communication of a child with profound disabilities when compared to that of a health professional.

In Steve's case, the caregiver did not perform better than the clinicians. In fact, no rater achieved better than chance categorization in the uninformed review, suggesting an apparent lack of visibly discernible patterns in Steve's responses. The poor visual discrimination of

responses may be attributed to the length of Steve's response, which was more than twice that of Billy's (14 s vs 6 s). The longer response times for Steve were due to caregiver uncertainty regarding his attempt to point. The discrepancy between the caregiver's preconceived notion of a typical deictic gesture and the actual visual appearance of the child's pointing may have fueled this uncertainty therefore creating longer response times and potentially masking the actual movement patterns. Nonetheless, the caregiver's intuition about Billy's communicative intent emphasizes the importance of caregiver perspective when decoding preference in children with profound disabilities.

### Merits of Systematic Characterization

When equipped with the movement patterns identified by the systematic characterization (Table V), clinician ratings improved from borderline fair to mid-range fair for the first client, Billy. This finding suggests that rigorous systematic assessment of communication (Green et al., 1997; Petry & Maes, 2006) may serve as a helpful adjunct to the visual classification of movement. In contrast, clinician ratings remained poor in the informed review of Steve's responses. The differential impact of the systematic characterization on visual detection of preference may be due to the differences in the children's individual typical responses. While Billy's typical response consisted of specific head and shoulder poses (limb positions), Steve's typical response consisted of more subtle changes in movement quality (limb accelerations). It has been suggested that the human visual system possesses independent mechanisms for processing spatial and temporal aspects of motion (Anderson & Burr, 1985). It could be argued that Billy's typical response consisted of spatial patterns, whereas Steve's typical response was more of a temporal pattern. Furthermore, there is evidence that the visual detection threshold for changes in the speed of a moving object (i.e., acceleration) is higher than the threshold for detecting a change in the direction of an object's motion (Werkhoven, Snippe, & Toet, 1992). This potential difference in human sensitivity to changes in position versus changes in speed may have favored clinician detection of Billy's typical response.

Nonetheless, in both case studies the automatic classification rates exceeded chance levels. Automatic preference classification was completed offline using accelerometric features determined via the systematic characterization. The above-chance classification rate is of particular interest for two reasons: First, for Steve, the systematic characterization did not identify obvious prototypical movements in the majority of responses but rather a subtler prototypical valence (effort) pattern. Second, the clinician raters were unable to visually classify Steve's response at better-than-chance levels. These findings suggest that the systematic visual analysis led to a judicious extraction of salient quantitative features.

### Significance

**Enhancing Communication.** The clinicians' ability to detect Billy's 'like' and 'dislike' responses improved once they were informed about specific movements to look for. Information gained in the systematic characterization may enhance the visual differentiation of preference and, in turn, may facilitate communication between the child and his or her communication partners. Note that the clinicians were not familiar with Billy prior to the session. It thus appears that if appropriately informed about a child's prototypical responses, clinicians do not necessarily require an extended period of time before being able to detect his or her movement-based manifestations of preference. Most importantly, the clinicians themselves do not have to be the ones doing the time-consuming systematic characterization. Indeed, it would be unrealistic to expect that every clinician would or could perform the systematic characterization. The present study suggests that only one individual needs to carry out the systematic characterization, and that many communication partners could then use the extracted information to enhance interactions with the child. The prototypical movements arising from the systematic characterization may serve as an educational template for caregivers to learn to identify like and dislike responses. This may also alleviate pressure on family members who are constantly relied upon as the channel between the child and clinicians. By increasing a child's communication partners, one would also expand the child's social network, thereby increasing his or her participation within the child's environment.

**Fostering independence.** In certain cases, the degree of HKM can impede a child's ability to access established access switches. In the absence of an established switch, the child may rely on caregivers to facilitate communication. The development of an access switch utilizing the accelerometer data could give this population a source of independent control. Children must develop independence skills in order to transition into new settings, such as going to school, without a familiar caregiver. In both case studies, the accelerometer-based classifier gave accuracies above 62%. The relatively small number of responses limited the number of features that could be used in the classifier. Moreover, only a simple Fisher-LDA was considered. The inclusion of more features and the implementation of nonlinear classifiers may further improve accuracies. Given that this is the first examination of communicative movement patterns amid HKM, accuracy results above 60% are very promising from an access technology perspective. Access to a movement-based switch would help these children to independently communicate with other students, teachers or caregivers unfamiliar with their movement patterns.

### Limitations

The proposed method necessitates that the child understands the cause and effect relation between his actions

(i.e. pointing at the *LIKE* sign) and the result (i.e. a video clip related to the image of interest begins). For some children with profound disabilities, such awareness has not been developed or learned helplessness (Jacobsen, Viken, & von Tetzchner, 2001) may have set in. Contingency awareness training may help these children to gain an appreciation of cause-and-effect relationships (O'Brien, Glenna, & Cunningham, 1994). The method described here relies on the child's willingness and ability to point, as a trigger for hyperkinetic movement. While the children examined here often had some means of communication (i.e., eye gaze or vocalization), typically their limbs had not played a role in communication. As a consequence, attempting to point may, in fact, be physically challenging for some children in this population. It is suggested that, in future studies, participants undergo full cognitive and communication assessments in order to determine the exact population that would benefit from this method.

The integrated method further requires that the child either does or does not like the stimuli presented, which implies that the results rely on the caregiver's ability to accurately select non-neutral stimuli, the child's comprehension of the stimuli, and the caregiver's ability to interpret the child's response. Additionally, there is a time lag between when the child initiates communication and when the caregiver responds, which could potentially dampen the characteristics of a response. The method relies on the child's engagement and caregiver's interpretation, and further work is needed in order to explore the best definition of a 'true response' that maximizes response reliability and validity.

Finally, the results from the systematic review of the videos were critical to the success of both the informed review and the feature extraction for automatic preference classification. Despite seeing success in both of these classifications, future work may consider using multiple reviewers for the systematic classification to test the inter-rater reliability. Likewise, one may consider eliminating the unclassified category in the informed review, so these results can be directly compared to the results from the accelerometer classification.

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## Notes

1.  $\pm 1.5\text{g}$ – $6\text{g}$  Three Axis Low-g Micromachined Accelerometer [Apparatus and software]. (2005). Chandler, AZ: Freescale.
2. 16-Bit, 250 kS/s M Series Multifunction DAQ, Bus-Powered [Apparatus and software]. (2009). Vaudreuil-Dorion, QB: National Instruments Corporation.
3. Labview 2009 [Computer software]. (2009) Vaudreuil-Dorion, QB: National Instruments Corporation.
4. Handycam Camcorders [Apparatus and software]. (2005). Toronto, ON: Sony of Canada Ltd.
5. MATLAB Statistics Toolbox (2009b) [Computer software]. Natick, MA: MathWorks.

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