Changes in the kinematic structure and non-kinematic features of movements during skilled reaching after stroke: A Laban Movement Analysis in two case studies

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Abstract

The purpose of this study was to adapt a universal language for human movement, Laban Movement Analysis (LMA), to capture the kinematic and non-kinematic aspects of movement in a reach-for-food task by subjects whose movements had been affected by stroke. Two control subjects, one stroke subject with internal capsule damage, and one subject with right posterior parietal stroke were video recorded while performing the reaching task. The movements of limb advancement, grasping the food, and limb withdrawal to place the food in the mouth, were notated using LMA. A scale, the Expressive Reaching Scale (ERS), was derived from the notation. All subjects completed the task; however, the stroke subjects displayed abnormalities in both the kinematic and non-kinematic aspects of movements during reaching with either limb. The most extensive impairments were in the contralateral-to-stroke limb and were most severe in the subject with internal capsule damage. The ERS rating scale may be a useful diagnosis and assessment tool.

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1. Introduction

Classification and diagnosis of motor disorders are based on experimental and clinical observations. For example, depending on the type of lesion, stroke can impair movements of the upper limb in reaching and grasping. The change in limb function can be measured in many ways, including end point measures such as success (Farr and Whishaw, 2002; Monfils et al., 2005), computerized kinematic analyses (Trombly, 1992; Platz et al., 2001; Cirstea et al., 2003a,b), through measures of muscle activity and synergy (Trombly, 1993; Lang and Schieber, 2004; Micera et al., 2005), applied grip forces (Boissy et al., 1999; Aruin, 2005), and standardized rating scales (Levin et al., 2004). The use of biomechanical analyses provides rigorous quantification of movement variables, such as muscle flexion and extension, limb pronation or supination, and coordination, and is a useful tool for clinicians and therapists to diagnose and design therapies for the changes in kinematic motor function after stroke. Nevertheless, there are non-kinematic changes in the movements of patients after stroke such as fatigue, increases in effort required to produce movement, and intrusive movements such as tremors, tics, and gestures that are more difficult to document (Jackson, 1932; Jeanerrod, 1988; Klein, 2005). An observer may recognize these non-kinematic changes in movement but may find them difficult to quantify.

One method of enhancing the classification of the symptoms of stroke is to use a formal ‘language’ for movement description which captures both the kinematic features of movement as well as the non-kinematic features. Laban Movement Analysis (LMA), derived from the study of dance, is a formal and universal language for human movement (Laban, 1960; Dell, 1966; Hutchinson, 1977; Bartenieff and Lewis, 1980) that has been applied to experimental research (Foroud and Pellis, 2003; Whishaw et al., 2003; Foroud et al., 2004; Vasey et al., in press).
press). LMA provides an analysis of both the kinematic and non-kinematic features of movement by categorizing movement descriptions into four components: Body, Effort, Shape, and Space. A full LMA analysis describes how the observed motor action uses the four components of movement, and how each component of movement is related to one another (Laban, 1960; Hutchinson, 1977; Bartenieff and Lewis, 1980; Foroud and Pellis, 2003; Whishaw et al., 2003; Foroud et al., 2004; Vasey et al., in press). The kinematic structure of movement is described through Body and Space, which provides a rich description of how the many spatial-temporal body and limb relationships change in relation to one another and to the environment. The emphasis of the Body and Space description is on how the changes occur, rather than what the changes are—as is the case with traditional kinematic measures. Non-kinematic features of movements are the seemingly qualitative aspects of movement that can be reliably categorized through observation by the study of LMA—Effort and Shape (Bartenieff, 1973; Bartenieff and Davis, 1973; Bartenieff, 1974; Fagen et al., 1997).

Effort and Shape capture the exertion of movement by providing a way of describing changes in the intensity, shape, force, flow and rhythm of movement. These changes are more expressive than changes in the spatial-temporal body relations, described by Body and Space, and can be influenced by many factors including the temperament of the mover, the situation he/she is in, and the environment (Bartenieff and Lewis, 1980). There are many anecdotal accounts of various non-kinematic changes in the movements of human stroke patients (Trombly, 1992) that remain unclassified and might pass relatively unnoticed in biomechanical analyses. LMA thus potentially provides a useful addition to conventional biomechanical descriptions of movement disorders as it can be used to classify the non-kinematic aspects of movement. At present, there have been no previous attempts to use formal languages to describe upper limb dysfunction in human stroke patients and no previous attempts to describe any neurological disorders using LMA.

The purpose of this study was to use LMA to analyze movements of two stroke subjects during a reaching for food task (Whishaw et al., 2002). The goal in this study is to provide a detailed enough description of skilled reaching after stroke that captures both kinematic and non-kinematic aspects of movement that can later be quantified into a standardized rating scale for use by those unfamiliar with the details of LMA. The comparison of two stroke cases, one mild and one severe, that remain unclassified and might pass relatively unnoticed in biomechanical analyses. LMA thus potentially provides a useful addition to conventional biomechanical descriptions of movement disorders as it can be used to classify the non-kinematic aspects of movement. At present, there have been no previous attempts to use formal languages to describe upper limb dysfunction in human stroke patients and no previous attempts to describe any neurological disorders using LMA.

The purpose of this study was to use LMA to analyze movements of two stroke subjects during a reaching for food task (Whishaw et al., 2002). The goal in this study is to provide a detailed enough description of skilled reaching after stroke that captures both kinematic and non-kinematic aspects of movement that can later be quantified into a standardized rating scale for use by those unfamiliar with the details of LMA. The comparison of two stroke cases, one mild and one severe, allows detailed movement analysis which when completed, can be generalized into a standardized rating scale. The derivative rating scale can be used in studies of a single patient, as might occur for occupational therapy, or in conventional research experiments. The first subject in this study suffered from a stroke causing damage to the parietal cortex. This subject was compared to the second stroke subject who suffered from middle cerebral artery stroke that had damaged the internal capsule, as well as two age-matched controls. Reaching movements were notated using LMA. From the notation, a rating scale called the Expressive Reaching Scale (ERS) was derived. This scale can be used as a diagnostic and assessment tool.

2. Materials and methods

2.1. Subjects

Subjects included two stroke subjects and two control subjects. All four subjects are right-handed adult males, two of whom were recovering from right hemisphere strokes which caused motor dysfunction on the left side of their bodies. The first stroke subject, had damage in the right posterior parietal lobe and the second stroke subject showed damage to the right posterior limb of the internal capsule. At the time of participation in this study, both stroke subjects were at the beginning of their occupational and/or physiotherapy program as outpatients at the rehabilitation clinic at the local hospital. The remaining two subjects were healthy age-matched controls for each of the stroke subjects. All the subjects provided informed consent to participate in the study and the study was conducted with the approval of the University of Lethbridge Human Subjects Ethics Committee and the Chinook Health Region.

2.1.1. Parietal lobe stroke subject (PL)

PL is a 59-year-old male who suffered from a stroke causing a lack of coordination of the left arm as well as numbness and weakness in the left arm and leg. CT scans indicated damage in the right superior posterior parietal cortex. At the time of participation in this study, the subject was independent, but was using a walker as a precaution. The control for PL was a right-handed 64-year-old male.

2.1.2. Internal capsule stroke subject (IC)

IC is a 72-year-old male recovering from a stroke that caused left-sided hemiplegia. A MRI showed damage in the posterior limb of the internal capsule. The subject uses a wheelchair and needs assistance with dressing and other tasks that require the use of both arms and/or legs. The control subject for subject IC was a 72-year-old right-handed male.

2.2. Reaching task

For the reaching task (Whishaw et al., 2002), subjects were asked to reach for a piece of food and place it in their mouth to eat. This is a natural behavior that is likely used daily by a subject and requires no special learning. The subjects were comfortably seated on a chair with a pedestal on an adjustable post positioned directly in front of them approximately 10 cm beneath their out-stretched palm. A food item was placed on the pedestal. At the beginning of the filming session, each subject was instructed to place both hands on their thighs, with their palms flat. Subsequent instruction consisted simply of telling the subject when to begin and which hand to use. When instructed to begin, a subject was expected to reach for the food item, place it in his mouth for eating, and then return his hand to his thigh. Due to anticipated patient fatigue in the stroke subjects potentially hampering the data collection, subjects were instructed to reach with one hand until two successful trials were completed, and then with the other hand for two successful trials. Subjects were given a
choice of one of four food items: smartie, raisin, gumdrop, or a shelled peanut.

2.3. Video recording

Canon 2R40 Digital Video Camcorders (30 frames/s) were for used video recording. One camera was placed in front of the subject so that a whole body view of the subject could be obtained. A second camera was placed in front of the subject and recorded the subject’s hand when it grasped the food item on the pedestal. Video was uploaded onto a G4 Macintosh computer and viewed in iMovie for a frame-by-frame analysis.

2.4. Procedure

Ipsilateral and contralateral to stroke limbs were compared between stroke subjects and to their matched controls. Data analysis was done using a LMA notation derivative called Motif and a movement rating scale – the Expressive Reaching Scale (ERS) derived from the notated scores. The observer/movement analyst (AF) holds a certification in Laban Movement Analysis and is experienced in both using and teaching LMA.

2.4.1. Laban Movement Analysis

LMA was developed for describing the kinematic or dynamic changes in the structure of movement (Body and Space), such as the changes in the relation of the body segments and spatial pathways or directions, as well as the non-kinematic, or expressive features of movement, such as the intensity, force, and rhythm of specific movements (Bartenieff and Lewis, 1980; Foroud and Pellis, 2003; Foroud et al., 2004; Vasey et al., in press). LMA emphasizes the processes underlying motor actions rather than the resultant motor action as the notation, or its shorthand derivative, Motif, records how the four movement components – Body, Effort, Shape, and Space (BESS) – are integrated, or not, throughout the observed movements. LMA was used in this study in order to provide an empirically derived description of the kinematic and non-kinematic movements made by stroke subjects during a reaching-to-eat task. The reliability of the non-kinematic measures in LMA has been validated in previous studies (Fagen et al., 1997; Foroud et al., 2004). Detailed descriptions of the components of LMA are described in Dell (1977), Hutchinson (1977), Bartenieff and Lewis (1980), and Maletic (1987). The following is an abbreviated description of BESS. For clarification, the first letter in LMA terminology is always capitalized.

2.4.1.1. Body. Body is the architecture defining the alignment relationships between anatomical segments during postural control and movement. The basic components of the body architecture are divided into the Upper (head/neck, chest/upper spine, shoulders/scapulae, arms/forearms/wrists/hands/fingers) and Lower Units (lower back/abdomen, pelvis/thighs/lower legs/feet/toes). Basic components can be divided in several different ways (i.e. midline and contralateral) according to the style of movement the mover is expressing (Fig. 1a). Depending on the way the subject moves, the body can also be expressed by the limbs, limb segments, and/or articulations (Fig. 1b). Body movements can also be categorized as Postural or Gestural. Postural movements involve the simultaneous movements of several basic components of the body that result in a shift in the centre.

Fig. 1. A diagram and LMA notation symbol index of the descriptors for LMA Body. (a) The basic components of the body architecture divided into Upper (head/neck, chest/upper spine, shoulders/scapulae, arms/forearms/wrists/hands/fingers) and Lower Units (lower back/abdomen, pelvis/thighs/lower legs/feet/toes). Basic components can be divided in several different ways: vertically across the midline, horizontally at the waist, and contralaterally. (b) The classification of the minor components of the body architecture by limbs, limb segments, and/or articulations (i.e. head, shoulder, upper arm, etc.).
of mass. Gestures are single actions involving the torso, head, limb, limb segments, or distal articulations.

2.4.1.2. Effort. Effort is the change in the intensity of exertion throughout movement. There are four types of Effort, called Effort Factors, Weight, Time, Space, and Flow. Each Effort Factor moves on a continuum moving from the powerful, resisting, fighting end of Condensing Efforts to the gentle, non-resistant, ‘going with the flow’, Indulging Efforts: Strong Weight to Light Weight, Quick Time to Sustained Time, Direct Space to Indirect Space, and Bound Flow to Free Flow (Table 1). Indulging Efforts are not limp or passive movement qualities; they are active qualities that are gentle. Limp or passive movements are not described by Effort analysis, they can be described by an LMA Body analysis as limp and passive movements are defined by the structural body movements’ relationship with an external force such as gravity. Although single Efforts can be performed alone, it is very difficult to produce a single Effort. Often Efforts are performed in combinations of two, three, and less often, four. Efforts are traditionally taught by a combination of verbal descriptions and movement experience in a dance studio. Therefore, in order to deepen his/her understanding of each Effort quality, the verbal definitions of the single Efforts, described below, are accompanied with some examples that the reader (dancer or not) is encouraged to experiment with. An exercise for each Effort quality is also provided. The following definitions and several of the examples are referenced from Bartenieff and Lewis (1980, p. 54–6).

The Weight Effort Factor is about creating impact through movement by changing the force or pressure exerted throughout a movement.

Strong Weight Effort (Condensing) is the increase of force or pressure throughout a movement. Smashing an object with a fist, playing forte on a piano, or beating a rug are some examples of Strong Weight Effort. Exercise: try moving your arm with a vigorous impactful and powerful quality as if the air is so thick you have to push through it.

Light Weight Effort (Indulging) is the release of force, or pressure, throughout a movement. Handling delicate bone china, wiping tears from a child’s eyes, or touching a newborn infant’s hair are some examples of Light Weight Effort. Exercise: try moving your arm with a delicate and airy quality as if it were a feather floating in the breeze.

The Time Effort Factor is the movers’ exertion of velocity throughout an action. Duration of time is irrelevant to Time Effort. That is, both Quick and Sustained Time Efforts can be used to make the same gesture in a one-minute time frame; it is the movers’ approach on how to use the time throughout the movement that is described by Time Effort.

Quick Time Effort (Condensing) involves acceleration throughout movement. Removing ones hand away from sudden contact with a hot stove, startled and darting out of someone’s way upon running into them from around a corner, or swatting a fly are some examples of Quick Time Effort. Exercise: try moving your arm with a sudden urgent and hasty quality as if you are catching mosquitoes in your palm.

Sustained Time Effort (Indulging) involves deceleration throughout movement. Embracing a close friend, getting up from a warm chair by the fire, or waving goodbye to a loved one are some examples of Sustained Time Effort. Exercise: try moving your arm with a lingering quality as if you want to savor every sensation in the action.

The Space Effort Factor is about how the body attends to the space it is moving in by attending to something specific or to everything at once.

Direct Space Effort (Condensing) is a pinpointed focused attention to the environment throughout a movement. Cracking an egg, plucking an eyebrow, or pointing to a specific target, are some examples of Direct Space Effort. Exercise: try moving your arm with a zeroing-in quality as if you are pointing out the needle you spotted in the haystack.

Indirect Space Effort (Indulging) is the multifocused attention to the environment throughout a movement. Folding beaten egg whites, waving flies out of the way, or scanning the parking lot for your car are some examples of Indirect Space Effort. Exercise: try moving your arm with a flexible and all-encompassing focus as if you wish to point to everything in the room in one gesture.

The Flow Effort Factor is about the quality of the progressive continuity of ones movement whether it is resisting flux or abandoning oneself to go with it.

Bound Flow Effort (Condensing) is an increase of constraining and restricting tension that is exerted throughout a movement. Arm wrestling with an equal match, walking in a dark and cluttered room, or making a gesture of cautious refusal, are some examples of Bound Flow. Exercise: try moving your arm in a restrained way so that you are prepared to stop moving at any moment as if you are trying to control the flow of movement by holding back.

Free Flow Effort (Indulging) is a release of constraining tension throughout a movement. Children playfully tumbling on a trampoline, or swinging a heavy object before releasing it (i.e. javelin) are examples of Free Flow Effort. Exercise: try moving your arm with a sense of abandonment and easy flowing ready-to-go-at-any-moment way as if you are playfully exaggerating your walk.

2.4.1.3. Shape. Shape is the exertion in the manner in which the body changes in posture to adapt to the surrounding environment throughout a movement. There are three ways in which Shape can change throughout a movement. (1) Directional Shape is the type of shape the body takes along a particular trajec-
tory. (2) Shapeflow is how the body responds to internal and/or external perturbations. Internal perturbations include changes in breath, emotions, and thoughts. External perturbations can be changes in stimuli (i.e. light, sound, etc.) and the relationship between self and the people in the environment. (3) Shaping is the qualitative changes in the shape of the body. There are six Shaping Qualities defined in LMA: Rising, Sinking, Spreading, Enclosing, Advancing, and Retreating. Shaping Qualities can be performed individually, or in combinations of two or three. Shaping is not equivalent to spatial orientation. For example, Rising is the quality of lifting regardless of direction of movement. One can sit down with a Rising Quality. The reader can do this exercise by pretending someone is gently pulling a strand of hair from the top of his/her head as he/she is in the process of moving from a standing position to sitting in a chair. Sinking, the opposite of Rising, is the quality of sinking, regardless of direction of movement. A person can walk up a staircase while sinking in the torso, as if someone is pulling down an imaginary string tied to the tip of the tailbone. Spreading is the quality of opening or expanding body volume. For example, when simultaneously yawning and stretching, the body expands in a Spreading Quality. Enclosing, the opposite of Spreading, is to gather inward. After yawning, the body Encloses. Advancing is the quality of approach or progression forward, despite direction of movement. Walking upstream in a rapid shallow creek requires the use of an Advancing quality. Retreating, the opposite of Advancing is to withdraw. A cautious or frightened person may step toward the source of fear with a Retreating quality.

2.4.1.4. Space. Space is the interaction between the body and the spatial environment. The environment is conceptualized as a geometric space constructed from the length, width, and depth of the body. These dimensions of the body represent the vertical, horizontal, and longitudinal directions the body can move through Space (Fig. 2). Space considers orientation (where you are in the room), movement trajectories (pathways), and spatial pulls (i.e. two simultaneous spatial pulls during one movement can be Upward and Forward).

2.4.2. Expressive Reaching Scale (ERS)
The ERS is a scale derived from the LMA notations of reaching made in this study (Table 2). This scale is novel to other rating scales used for skilled reaching as it provides a method for quantifying the exertion of the movement by assessing the non-kinematic features of movement that have a more expressive quality than the kinematic structure of movements. The ERS evaluates four phases of the reach-to-grasp task: Advance, Grasp, Withdrawal, and Release. Each major component should be performed in one action (gesture) and contains subcomponents resulting in an overall total of 23 subcomponents (Table 2). The 23 subcomponents of the ERS are descriptions of the
2.4.2.2. Non-kinematic components.

2.4.2.2.1. Hand appears to be stuck on the pedestal. After grasping the target, the hand should lift-up without resistance. Upon grasping, if the hand seems to resist lifting and appears to be too heavy to lift, or stuck on the pedestal a score of 0.5 is given. If the hand seems to be stuck on the pedestal while the subject seems to be actively (grunting, clenching, flexing, breathing heavily, and twisting the body) trying to lift or move the hand away from the pedestal, a score of 1 is given. The length of time it takes to lift the hand after grasping is irrelevant to this component of the rating scale. Instead, it is the effort exerted to lift the hand upon grasping that is to be scored (Table 2; point 10).

2.4.2.2.2. Efforts. Normal reaching requires the use of Direct Space Effort toward the end of the advance. A person may use Light Weight or Quick Time Efforts during the advance or withdrawal phases to increase the smoothness of the behavior. Other than Direct Space, the following Effort Qualities can hinder the performance of the task.

Strong Weight Effort (Condensing) is the increase of pressure throughout a movement. A score of 1 is given if the subject uses Strong Weight during the (A) advance or (C) withdrawal (Table 2; points 3, 15 and 21). If the subject is using Strong Weight Effort, it will look like he/she is pushing or lifting something heavy.

Indirect Space Effort (Indulging) is the multifocused attention to the environment throughout a movement. A score of 1 is given if Indirect Space is observed during the (A) advance or (C) withdrawal (Table 2; points 4 and 16). If Indirect Space Effort is used, it will look as though the subject is moving his/her arm in the dark towards an object that the approximate position in space is known.

Direct Space Effort (Condensing) is a pinpointed focused attention to the environment throughout a movement. A score of 1 is given if Direct Space is NOT used toward the end of the (A) advance (Table 2; point 5). If the subject is using Direct Space Effort, it will appear that his/her arm aims clearly towards the target throughout the movement.

Bound Flow Effort (Condensing) is an increase of constraining and restricting tension that is exerted throughout a movement. A score of 1 is given if the subject uses Bound Flow during the (A) advance, (B) grasp, or (C) withdrawal (Table 2; points 6, 11, 17, and 22). If Bound Flow Effort is used, it will look like the subject is resisting the movement—as though the body/arm is being held back.

2.4.2.2.3. Shaping Qualities. A score of 1 is given if the subject uses any one or combination of Shaping Quality(ies) with the torso during any phase of the reach (Table 2; points 7, 12, 18, and 23). If Rising and/or Sinking Qualities are used, the subject may look like he/she is trying to lift and/or is slumping the body. If Spreading and/or Enclosing Shaping Qualities are used, the subject may look like he/she is moving in a writhing or contorted way. If Advancing and/or Retreating Qualities are used, it may look like the subjects torso is being pulled forward or backward.

For each subcomponent, a score of 0 was given in the complete absence of the movement/movement quality; a score of 1 was given if the movement/movement quality was made; and if the movement, or movement quality, was present, but only partially, or at a low intensity, a score of 0.5 was given.

### Table 2
The Expressive Reaching Scale (ERS)

<table>
<thead>
<tr>
<th>Major components</th>
<th>Subcomponents</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Advance</td>
<td>1 Uses more than one gesture</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>2 Limb moved by body/torso</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>3 Strong Weight Effort observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>4 Indirect Space Effort used at the end of the advance</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>5 Direct Space Effort not used at the end of the advance</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>6 Bound Flow Effort observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>7 Shaping Qualities observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td>B. Grasp</td>
<td>8 Uses more than one gesture</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>9 Hand moved by body/torso</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>10 Hand appears to be stuck on the pedestal</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>11 Use of or increased use of Bound Flow Effort</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>12 Shaping Qualities observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td>C. Withdrawal</td>
<td>13 Uses more than one gesture</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>14 Limb moved by body/torso</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>15 Strong Weight Effort observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>16 Indirect Space Effort used at the end of the withdrawal</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>17 Bound Flow Effort observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>18 Shaping Qualities observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td>D. Release</td>
<td>19 Uses more than one gesture</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>20 Limb moved by body/torso</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>21 Strong Weight Effort observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>22 Bound Flow Effort observed</td>
<td>0, 0.5, 1</td>
</tr>
<tr>
<td></td>
<td>23 Shaping Qualities observed</td>
<td>0, 0.5, 1</td>
</tr>
</tbody>
</table>

inappropriate movements that contribute to reaching abnormally. For each subcomponent, an individual can receive a score of 0 (movement description not observed), 0.5 (movement description partially observed), or 1 (movement description fully observed). A maximum score of 23 points would be a poor performance.

2.4.2.1. Kinematic components.

2.4.2.1.1. Uses more than one gesture. A gesture is one action made by one limb or one limb segment. A normal reach consists of four gestures: (A) advance (arm), (B) grasp (hand), (C) withdrawal (arm), and (D) release (arm). Any additional gestures made by any body part during these primary gestures receives a scores of 1 (Table 2; points 1, 8, 13, and 19).

2.4.2.1.2. Limb moved by body/torso. The gesture of moving the arm during reaching should be made independently of the torso. Although the torso may make supporting contralateral movements, it should not carry the arm. A score of 1 is given if the subject uses the torso to move the reaching/grasping limb during the (A) advance, (B) grasp, (C) withdrawal, or (D) release (Table 2; points 2, 9, 14, and 20).

2.4.2.2. Non-kinematic components.

2.4.2.2.1. Hand appears to be stuck on the pedestal. After grasping the target, the hand should lift-up without resistance. Upon grasping, if the hand seems to resist lifting and appears to be too heavy to lift, or stuck on the pedestal a score of 0.5 is given. If the hand seems to be stuck on the pedestal while the subject seems to be actively (grunting, clenching, flexing, breathing heavily, and twisting the body) trying to lift or move the hand away from the pedestal, a score of 1 is given. The length of time it takes to lift the hand after grasping is irrelevant to this component of the rating scale. Instead, it is the effort exerted to lift the hand upon grasping that is to be scored (Table 2; point 10).

2.4.2.2.2. Efforts. Normal reaching requires the use of Direct Space Effort toward the end of the advance. A person may use Light Weight or Quick Time Efforts during the advance or withdrawal phases to increase the smoothness of the behavior. Other than Direct Space, the following Effort Qualities can hinder the performance of the task.

Strong Weight Effort (Condensing) is the increase of pressure throughout a movement. A score of 1 is given if the subject uses Strong Weight during the (A) advance or (C) withdrawal (Table 2; points 3, 15 and 21). If the subject is using Strong Weight Effort, it will look like he/she is pushing or lifting something heavy.

Indirect Space Effort (Indulging) is the multifocused attention to the environment throughout a movement. A score of 1 is given if Indirect Space is observed during the (A) advance or (C) withdrawal (Table 2; points 4 and 16). If Indirect Space Effort is used, it will look as though the subject is moving his/her arm in the dark towards an object that the approximate position in space is known.

Direct Space Effort (Condensing) is a pinpointed focused attention to the environment throughout a movement. A score of 1 is given if Direct Space is NOT used toward the end of the (A) advance (Table 2; point 5). If the subject is using Direct Space Effort, it will appear that his/her arm aims clearly towards the target throughout the movement.

Bound Flow Effort (Condensing) is an increase of constraining and restricting tension that is exerted throughout a movement. A score of 1 is given if the subject uses Bound Flow during the (A) advance, (B) grasp, or (C) withdrawal (Table 2; points 6, 11, 17, and 22). If Bound Flow Effort is used, it will look like the subject is resisting the movement—as though the body/arm is being held back.

2.4.2.2.3. Shaping Qualities. A score of 1 is given if the subject uses any one or combination of Shaping Quality(ies) with the torso during any phase of the reach (Table 2; points 7, 12, 18, and 23). If Rising and/or Sinking Qualities are used, the subject may look like he/she is trying to lift and/or is slumping the body. If Spreading and/or Enclosing Shaping Qualities are used, the subject may look like he/she is moving in a writhing or contorted way. If Advancing and/or Retreating Qualities are used, it may look like the subjects torso is being pulled forward or backward.
3. Results

All control and stroke subjects were able to complete the reach successfully by picking up the food item and placing it in their mouths. Furthermore, all subjects except for IC, successfully completed the task on every trial. IC also completed the task on every trial when reaching with the ipsilateral-to-stroke arm, however, when reaching with the contralateral-to-stroke arm, IC failed at several attempts. The control subjects showed individual differences in some fine aspects of their movement, however, the majority of the motor components of the task were performed similarly. Both PL and IC showed a variety of abnormal movements when reaching with either their ipsilateral- or contralateral-to-stroke arms. The severity of motor symptoms was greater in their contralateral arms. IC displayed the greatest severity and it took several more attempts for IC to complete two successful reaches with the contralateral-to-stroke arm. He completed the task successfully on his fourth and seventh trial. On his first trial, IC rested with his reaching arm on his lap after grasping the target and used his other hand (ipsilateral) to reposi-tion the target in the reaching hand before bringing the target successfully to his mouth. He dropped the target upon grasping it on his second and fifth trials, and he dropped the target at his mouth on his third and sixth trial. Fig. 3 provides an example of the Motif scores of the reaching task performance from this study.

3.1. Expressive Reaching Scale (ERS)

Three of the four subjects scored above the perfect score of 0 on the ERS. The control for PL had a mean of 1 with the right arm and a mean of 1.5 out of 23 with the left arm (Fig. 4). When reaching with either arm, he used some non-kinematic movements (Efforts) that are inappropriate for the reaching task during the advance and withdrawal portions of the reach. The control for IC scored 0 out of 23 with either arm, therefore showing no errors on the ERS (Fig. 4).

PL scored a total of 1.5, when reaching with the ipsilateral arm. When reaching with the contralateral arm, he scored a total of 6.25, showing the use of both kinematic and non-kinematic...
movements that are inappropriate for the reaching task during the advance, grasp, withdrawal and release components of the ERS (Fig. 4). IC scored a total of 5 with the ipsilateral arm showing the use of both kinematic and non-kinematic movements that are inappropriate for the reaching task in every component of the scale. When reaching with his contralateral-to-stroke arm,

IC scored a total of 17 and showed greater differences in his use of inappropriate kinematic and non-kinematic movements for the reaching task during the advance, grasp, withdrawal, and release components of the scale on successful reaches (Fig. 4). The ERS was also used to analyze two unsuccessful reaching trials and one incomplete reaching trial by IC when reaching with his contralateral-to-stroke arm. On the two unsuccessful trials scored, IC completed every portion of the reach, but either used his right (ipsilateral-to-stroke) arm to adjust his grasp of the target, or lost the food target when it was near his mouth. The average score on the ERS on these two trials was 17.75. On the incomplete trial that was scored, IC dropped the target upon grasping it, and so, rather than completing the task, he returned his reaching arm to the starting position. Therefore, the withdrawal component of the ERS was not applicable as IC did not perform it. On this incomplete trial, IC received a score of 10 out of 17 applicable potential points. Fig. 5 summarizes overall scores and compares the kinematic versus non-kinematic impairments captured by the ERS. In all cases, the non-kinematic impairments are higher than the kinematic ones.

3.1.1. PL

When reaching with the ipsilateral arm (right), PL was slightly rigid (Bound Flow Effort) and used too much pressure (Strong Weight Effort) throughout the withdrawal portion of the reach. When reaching with the contralateral arm (left), PL consistently demonstrated the following abnormalities as highlighted in Fig. 6:

3.1.1.1. Kinematic components. The reaching limb was moved by body/torso. The limb was lifted then carried forward towards the target by leaning forward with the torso during the advance. During the withdrawal, the torso carried the reaching limb as the torso leaned back, away from the pedestal. Once the torso was returned to the natural upright position, the reaching limb lifted the hand towards the mouth.

3.1.1.2. Non-kinematic components. Several inappropriate Effort Qualities were observed throughout the gestures in the
reaching task. The subject gave the appearance that, rather than reaching for a small food item, he was using his arm to push a heavy object (Strong Weight Effort). Although the trajectory of the arm was a direct route toward the target, the way the arm moved along the trajectory was multifocused, as if the subject were reaching in the dark (Indirect Space Effort). Throughout the reaching task, the subject showed an increase of constraining and restrictive tension (Bound Flow) as if his muscles were too rigid or tight to perform the task smoothly.

3.1.2. IC

When reaching with the ipsilateral arm (right), IC had mild abnormalities in every major component of the ERS. He exerted more pressure (Strong Weight Effort) than necessary throughout the advance and release. He was rigid (Bound Flow Effort) during the advance, grasp and withdrawal. During the grasp, rather than lifting his hand without resistance, his hand lingered on the pedestal; and he made more than one gesture during the release. When reaching with the contralateral arm (left), IC had the following abnormalities as highlighted in Fig. 6:

3.1.2.1. Kinematic components. The subject made several gestures during each component where only one gesture is necessary for normal movement (Fig. 6). By raising the torso and leaning forward, the subject allowed the reaching limb to be carried toward the target on the advance. Upon grasping the target with his fingertips, the subject’s hand appeared stuck to the pedestal. During the grasping component, the subject leaned forward and twisted his torso in order to slide his hand off the pedestal. The subject actively tried to lift or move his hand away from the pedestal. It took great force for him to slide his hand off it. During the withdrawal, IC simultaneously lifted his torso and leaned backward so as to move the limb away from the pedestal. At this point, his head was carried by the movement of his torso as the distance between the hand and the mouth remained constant. Once his hand was away from the pedestal (an action that requires a simple lifting up of the hand in control subjects), IC attempted to bring the food target to his mouth. At this point, he lowered his head as his torso continued to move backward. During this time, the
distance between the torso and limb became smaller, but it then remained constant as IC continued to lean backwards with his torso. The continuation of leaning backwards while maintaining a fixed distance between the hand and the mouth prevented IC from successfully bringing the food item to his mouth. He then twisted his torso in an attempt to bring his mouth closer to his hand. Finally, after swaying slightly from side-to-side, the subject managed to bring his mouth to his hand and eat the food target.

3.1.2.2. Non-kinematic components. Several inappropriate Effort Qualities, similar to PL, were observed throughout IC’s gestures when reaching with his contralateral arm. Like PC, IC gave the appearance that, rather than reaching for a small food item on the advance and release, he was using his arm to push a heavy object (Strong Weight Effort); and during the advance it was as if he was reaching in the dark (Indirect Space Effort). These types of movement qualities were accompanied with increasing constraint (Bound Flow). IC’s arm never reached the target with a pinpointed direct focus (lack of Direct Space Effort).

In addition to using inappropriate Effort Qualities, IC used Shaping Qualities that are not necessary for performing the reaching task with efficiency. During the advance, IC displayed Rising (lifting), Spreading (expanding body volume), and Advancing (approaching) qualities. During the grasp, Rising, Sinking, and Spreading Shaping Qualities were observed and seemed to interfere with the ease of grasping and lifting the target. During the withdrawal, the subject displayed Rising, Enclosing, and Retreating; all three qualities that hinder the normal withdrawal gesture.

3.1.2.3. Unsuccessful reaching trials. On the two unsuccessful reaching trials IC performed the movements in a similar fashion as the successful trials described above. The one difference between these trials and the successful trials was observed on the one unsuccessful trial when IC dropped the target at his mouth. On the release component of this trial, IC did not use any of the Effort qualities as he did on the other trials. Furthermore, on a third incomplete trial, IC accumulated points as he made similar inappropriate kinematic and non-kinematic movements in the advance and grasp components of the task to the ones made during the other trials. However, although he performed the release component, he did not use any of the Effort qualities on this portion.

4. Discussion

The present study produces a LMA description of skilled reaching that captures the kinematic and non-kinematic features of movements that may change after stroke in human subjects. Based on this description, a rating scale, the ERS, was created in order to measure the skilled reaching-for-food movements. Results from the rating scale showed that the kinematic and non-kinematic changes in movement were greater in the contralateral-to-stroke limb than in the ipsilateral-to-stroke limb in the stroke subjects, and more severely in the subject with the internal capsule injury—which is known to produce severe motor impairments. These results indicate that LMA analysis and the ERS rating scale is sensitive to both the severity and the location of stroke and that the ERS provides a simple tool that can be used for diagnosis and assessment.

LMA is unique in its application because, whereas biomechanical analyses are used to simultaneously quantify the movements isolated body segments are making, LMA places emphasis on underlying motor patterns by noting how the body segments are moving, how they are supported, or affected, by other body parts, as well as whole body movement. Furthermore, LMA provides a language for describing the non-kinematic aspects of movements that cannot be captured by biomechanical analyses. This is the first study that provides a language for classifying the non-kinematic features of movements in any neurological patient, including stroke. Insights can be gained from using an analysis system such as LMA, as it identifies the underlying motor patterns (kinematic and non-kinematic) that effect actions that can be difficult to measure using biomechanical analyses. Such an understanding of the mechanisms underlying abnormal motor patterns in stroke patients is critical for designing effective rehabilitation programs (Lough et al., 1984; Cirstea and Levin, 2000).

Skilled reaching was used in the present study because reaching for objects, and especially reaching for food items to eat, is a daily activity, which, when lost or impaired, can compromise independence. The task has also been used in previous preclinical (Adkins and Jones, 2005; Hsu and Jones, 2005; Maclellan et al., 2005; Piecharka et al., 2005; Windle and Corbett, 2005; Gharbaree et al., 2006) and clinical investigations of stroke (Cirstea et al., 2003a,b,c; Roby-Brami et al., 2003a,b; Michaelsen et al., 2004; Michaelsen and Levin, 2004; Harris-Love et al., 2005; McCrea et al., 2005; Micera et al., 2005) and analogous tasks are widely used in studies of motor systems (Whishaw et al., 2002, 2003; Wallace and Whishaw, 2003; Whishaw, 2003; Field and Whishaw, 2005; Smith and Metz, 2005; Webb and Muir, 2005; Doan et al., 2006). Furthermore, the movements of skilled reaching in both normal subjects and patients are extremely consistent from trial to trial and between limbs, thus necessitating the use of only one, or at most, a few trials of data collection (Whishaw et al., 2002). The simplicity of the task thus lends itself to clinical studies where patient fatigue may hamper data collection and when time may be a constraint.

During the reaching-to-eat task, the kinematic structure (Body and Space) of movements work to support the action while the non-kinematic movements (Effort and Shape) are economized so as to minimize work effort. The kinematic structure of movement is the movement of the body through space—that creates the ‘scaffolding’ for movement that is the functional element of any task. While non-kinematic features of movements appear to be more qualitative and expressive, there are actions that benefit from an increase in non-kinematic movements. For example, the exaggeration of intensity, shape, force, flow, rhythm and attention emerge during sport or labor as well as during emotion, e.g. joy, sorrow, aggression, play, etc. These non-kinematic aspects of movements, thought to be more variable between people than the kinematic aspects of movement.
(Bartenieff and Lewis, 1980) can not only facilitate, but also hinder the efficiency of a motor behavior (Bartenieff and Lewis, 1980). Changes in the behavior of non-kinematic movements can occur after stroke due to fatigue (Jeanerrod, 1988), compensatory strategies (Lough et al., 1984; Cirstea and Levin, 2000; Roby-Brami et al., 2003a; Levin et al., 2004; Michaelsen et al., 2004), or released movements (Jackson, 1932). Though problems in the organization of the limbs during skilled actions after stroke are more typically described using biomechanical measures (Trombly, 1992, 1993; Platz et al., 2001; McCrea et al., 2002; Cirstea et al., 2003a,b,c; Lang and Schieber, 2004; Micera et al., 2005), LMA can describe, simultaneously, both the kinematic and non-kinematic features of movement and their interaction.

Two types of changes in the kinematic structure of movement were observed in the stroke subjects. First, the stroke subjects made extraneous gestures. A gesture is one action made by one limb or one limb segment and can involve a simultaneous movement of the limb, limb segments, or articulations. During reaching, both stroke subjects made more gestures than the healthy subjects. The extra limb gestures are repeated attempts of the specific component of the reach in which the stroke subjects failed. Second, rather than making the appropriate lateral movements in normal reaching, both subjects developed a new strategy for moving the torso to aid in performance of the task. During the advance and withdrawal, the subjects carried the limb to the desired target by making large forward and backward movements with the torso, rather than moving the arm independently. Using the torso to carry the arm to a desired target may be due to the lost, or newly limited, ability to move the arm independently of the torso. For example, the forward and backward movements of the torso were less pronounced in PL partly because he began the advance by lifting his arm independently of the torso, but then relied on his torso to continue to bring the arm towards the target.

Following stroke, many tasks can still be achieved; however, they are accomplished by the use of compensatory strategies (Lough et al., 1984; Cirstea and Levin, 2000; Roby-Brami et al., 2003a,b; Michaelsen et al., 2004), such as repeated gestures with gross motor support of the torso, rather than a series of smooth single gestures supported by subtle postural shifts as shown in this study (also see Trombly, 1992; Whishaw et al., 2002). In this study, the stroke subjects made multiple gestures within various components of the task to compensate for the inability to guide the arm properly toward the target. Furthermore, they used forward and backward movements of the torso, during the advance, grasp, and withdrawal, so as to bring the arm towards the desired location. The lost ability to gesture with the arm independently of the torso changed the function of the torso where making the appropriate lateral movements in normal reaching would have hindered the success of the overall reaching task.

There are two categories of non-kinematic features of movement that, in the stroke subjects, hindered their ability to reach for and eat a food target in a smooth manner. First, the Effort qualities listed in the ERS were inappropriate for the functional goal-directed task of skilled reaching. During reaching, both stroke subjects moved with unclear trajectories (Indirect Space) and increasing pressure (Strong Weight Effort) and tension (Bound Flow Effort)—three qualities that hinder the ability to reach efficiently. The intensity of these inappropriate Efforts was greater in the IC stroke subject, suggesting that the severity of released movement qualities and/or fatigue is related to the location of stroke. Alternatively, the greater intensity could have resulted from the expression of the difficulty of the task, or even from a perception that the task is difficult, thus further hindering the ease of the task. Indeed, even IC’s first attempt at the reaching task appeared to be extremely difficult for him and took him a great deal of effort. In contrast, PL seemed to perform the task with much less difficulty, even though his movement lacked fluidity and smoothness. In LMA theory, it is argued that some actions move in a “...continuous flowing progression...” (Bartenieff and Lewis, 1980, p. 51) with no specific exertion and that the movers mood or particular situation can change the use of Effort qualities by reducing or increasing in intensity or exertion, or by changing in proportionality, for effective function and expression (Bartenieff and Lewis, 1980). Reaching-to-eat appears to be an action where the use of Effort is minimal and restricted to being light, quick and direct. Following stroke, there appears to be a change in the type of Effort qualities used as well as an increase in the intensity. During the unsuccessful trial when the target was dropped prior to placing it in the mouth, and the incomplete trial when the target was dropped upon grasping, IC made the same kinematic movements to return his hand to his lap as in his other trials. However, he did not use the Effort qualities that were used during his other trials. This suggests that he is capable of moving his arm to place his hand on his lap without the dysfunctional use of Efforts. When moving within the framework of the task, however, he uses Efforts in a dysfunctional way. Therefore, studies on the influence of performing a formal task and the use of Effort qualities may be useful. The second type of non-kinematic movement that hindered reaching, Shaping, was most striking in the IC patient. IC shaped his body into various Shaping qualities. These movement qualities looked awkward and out of context because they were not consistent with the direction of the movement. For example, when leaning forward, IC engaged in a “Rising” quality, which, if anything, should have been an “Advancing” quality.

The ERS is the first scale that categorizes the non-kinematic movements and summarizes the relation between non-kinematic movements and the kinematic structure of the movements. In any task, the function of movements is maximized by capitalizing on the kinematic structure of the movements required and exerting only the minimum amount of non-kinematic movements. The out-of-context, non-kinematic movements displayed by the stroke subjects during reaching may be an example of the type of released movements that occur after stroke (Jackson, 1932). Furthermore, following brain injury, a patient frequently displays fatigue and weakness (Bourbonnais and Vanden Noven, 1989; Jeanerrod, 1988; McCrea et al., 2005). Although weakness may be attributed to the damaged physiology of the motor system (Bourbonnais and Vanden Noven, 1989), the dysfunctional use of Effort and Shaping Qualities after stroke can contribute to fatigue as it requires more energy and hinders the functionality of the actions. Nonetheless, the use of non-kinematic movements...
becomes abnormal after stroke and this study provides the first language for the classification of such movements in any task, as well as a new diagnosis and assessment tool that captures non-kinematic movements during reaching. The ERS and LMA can be used in future studies of the organization of non-kinematic movements, as well as to provide new insights on the behavior of tics, tremors, and other motor phenomena.

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References

Lang CE, Schieber MH. Reduced muscle selectivity during individuated finger movements in humans after damage to the motor cortex or corticospinal tract. J Neurophysiol 2004;91:1722–33.


