Upper limbs biomechanics: drinking evaluation protocol in hemiparetic patients

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Abstract. Biomechanical measurements applied to upper limbs gesture, characterisation and clinical evaluation are less diffused than lower limbs evaluation where gait analysis is rather common. When dealing with upper limbs a set of critical problems have to be afforded. In walking analysis we know that the movement is cycled and repeatable, instead upper limb gestures are more complex principally because of lack of the periodicity. In this paper we present a protocol to face such problems and obtain an objective biomechanics evaluation of the upper limbs, with the particularity to be focused on a daily life gesture such as drinking. The experimental protocol is presented together with the parameter identified to characterise the movement. Some preliminary results are discussed with reference to a set of healthy and clinical subjects.

1. Introduction
Stroke is the most common neurological disease in the adult population worldwide [1]. Since often brain area affected by stroke is the motor control section, one of the most common consequences is hemiparesis, defined as muscular weakness or partial paralysis restricted to one side of the body. For this reason, beside standing and walking, also grasp and manipulation movements are critical in stroke patients. However, the ability to reach, grasp, transport and release objects is essential for daily activities, such as feeding and grooming. Rehabilitation protocols are applied as soon as possible after the injury to maximise recover possibilities.

As regards the evaluation of patients’ biomechanics before, during or at the end of rehabilitation protocol, some biomechanical evaluation protocols are available for gait and walking analysis [2], and a few are available for upper limbs [3]. Beside that while gait and walking are natural daily life gestures, in general the evaluation of upper limb biomechanics is based on reference gestures such as pointing, grasping or hand to mouth [4]. Such movements are not the usual ones, they just mimic common daily life activities, so the patient may be less motivated and the evaluation is not directly related to subject autonomous capabilities in daily life [5].

The focus of this work is the design and test of a three-dimensional upper limbs biomechanical assessment system to quantify the injury and the progress during stroke rehabilitation. The reference gesture we have selected is based on a Reach to Grasp Cycle, but it is modified by also considering the drinking gesture. This motion sequence is very important in daily activities and incorporates all major
joints off the upper limb and simulates a functional task that is feasible, yet challenging enough to reveal key motor deficits in individuals with movement disorders [6]. The experimental protocol includes kinematics measurements by a three dimensional infrared video system, referred to a biomechanical model. The protocol includes the possibility to introduce surface electromyography measurements to evaluate muscular activations of the subject. Gesture performance can be evaluated both through time histories and spatial or temporal features. Moreover, an interesting approach for grasp evaluation is proposed: the hand area time history. It can give information on hand opening - closing subject’s capabilities [7]. The proposed protocol has been tested on a group of healthy subjects in order to construct a healthy reference range, useful to evaluate patients’ results.

2. Experimental protocol

2.1. The reference cycle
The subject is initially asked to sit comfortably on a chair placed in front of a table, as in figure 1. Hips and knees are flexed 90° and both feet lay flat on the ground. Both arms are at rest on the table so that the shoulder is in a neutral position, elbows are flexed, forearms are pronated, and wrist is held in a neutral position, with hand palms flat on the table. A water bottle (half a litre, only 1/3 filled) is placed on the table in front of the subject at 80% of the maximum reach distance.

![Figure 1. Initial position of the reference cycle.](image)

The cycle starts with the subject moving one limb to reach the bottle, grasp and bring it to mouth to simulate drinking; then back to table to release bottle in the same point of table and return to the initial position. Soon after the same cycle is repeated with the other limb. The healthy subjects were instructed to start with the dominant limb while patients start with the healthy limb.

The task is paradigmatic since it includes two relevant phases: a first open-chain movement (reaching for the bottle) and a second movement (bringing the glass to the mouth) where a strict coordination among upper limb, trunk and head movements is required, thus challenging the motor control system even in presence of upper limb minimal disability.

2.2. Biomechanical Model
We have designed a new biomechanical model, based upon Rab’s upper limb protocol [8], with some modifications due to the specificity of the task we are going to study. It requires 23 retroreflective skin markers: 4 on the head, 3 on the trunk, 4 for each forearm, 4 for each hand. Two additional markers are positioned on bottle top and bottom.

A procedure was defined in order to guarantee proper and reproducible marker positioning. A graphical representation of the biomechanical model is presented in figure 2. The red marker is positioned on subject’s chin in order to evaluate the accuracy of the drinking gesture, while on the hand there are markers on thumb, index and little finger nails to evaluate the hand’s opening and closing movements.
2.3. **Participants**
We experimented the protocol on 10 healthy subjects and 8 hemiparetic patients, of which two with right and six with left hemiparesis, at different injury levels, but always capable to conduct the test. All of them were informed and agreed to participate to the experimentation. Initially the protocol was checked on healthy subjects as a control group following a dual purpose: on one hand to have data on healthy subjects on the other to validate the protocol and the parameters set obtained. This preliminary data set was useful to identify movement strategies and associated joint angles histories to create a normality band.

2.4. **Acquisition sequence**
As already mentioned, the two limbs perform the gesture alternatively. Moreover, in order to evaluate subject’s repeatability, a set of five consecutive repetitions is required. According to subject’s availability and fatigue state, another set of sequences might be acquired, up to an overall of 5 sets. A short pause of approximately 2 minutes is planned between each set trial. The complete recording session lasts about half an hour for each subject. This is not a difficult task for a healthy subject but it may be complex for an injured one, according to the stroke consequences importance.

| Table 1. Dirking cycle characterisation parameters. |
|-----------------------------------------------|
| **Parameter** | **Unit** | **Description** |
| Temporal | Cycle time | s | Cycle duration in seconds |
| Mean velocity | m/s | Cycle mean velocity |
| Spatial | Trajectory length | m | Length of the curve tracked on the index finger |
| ROM | deg | Range of Motion of involved articulations, for each degree of freedom |
| Compensation | deg | Degrees of compensation movements of head and trunk |
| Grasp adjustment | Cycle fraction | Δ% | Fraction spent in adjusting the hand approaching the bottle |
| Target adjustment | Cycle fraction | Δ% | Fraction spent in adjusting the bottle on the target (mouth) |
| Grasp On target | Cycle moment | % | Cycle instant at which the bottle is grasped |
| | Cycle moment | % | Cycle instant at which the bottle is properly on the target |
| Hand | Max aperture | % | Ratio of maximum hand area on hand area at rest |
| Carrying | % | Ratio of hand area during carrying to mouth on hand area at rest |
2.5. Data processing

Three-dimensional kinematic data are acquired by a motion capture optoelectronic system, BTS Bioengineering GaitLab System, able to automatically record 3D trajectories of passive markers by means of stereo photogrammetric methods using 6 IR cameras. Marker’s positions measurements and their tracking is carried out in BTS environment with manual correction of eventual error or missing. Kinematic data enables the biomechanical analysis, that starts with the identification of a standard cycle, in order to be able to compare gestured carried out with different speeds, for example by healthy and injured subjects.

The velocity of the index finger marker defines the beginning and the end of the drinking cycle. The onset of movement from the resting start position is identified as the first instant when the normalized velocity of the index finger marker exceeds 5% of peak reaching velocity [9], while the end of the cycle is signified by a decrease in the same marker velocity to less than 5% of the maximum velocity upon returning to the initial position.

The biomechanical model consists of 11 segments (head, trunk, right and left upper arm, right and left lower arm, right and left hand, right and left fingers and bottle) whose local coordinate systems are used to calculate upper limbs motion [10]. A standard biomechanical analysis is applied to each segment obtaining Euler angles useful to determine the three-dimensional joint angles. Articular angles are used to express the joint angles of the proximal segment respect to the distal segment, following the biomechanical usual convention for rotation succession: flexion/extension, adduction/abduction and axial rotation. The segments of the head, the trunk and the bottle are described with references to the lab coordinate system. The shoulder joint is modelled as a ball and socket joint with three-degrees-of-freedom, located in the centre of the humeral head. Movement is calculated between the trunk and the humerus. The elbow joint is modelled as a rotating-hinge with two-degrees-of-freedom like the wrist, but this last one is modelled as a universal (saddle) joint. Moreover we have also defined a fingers’ joint as a hinge joint in order to calculate fingers’ flexion/extension movements.

A set of time or cycle histories is available for detail studies, while a set of overall spatial and temporal parameter is computed to obtain a simpler characterisation of the gesture and easier comparison between subjects. The parameters available at present moment are presented in table 1.

2.6. Hand’s surface area analysis

Among gesture parameters an interesting and rather new one is based on the idea that hand opening could be described by the surface area [7] defined by interconnecting the markers positioned on subject’s hand. In particular, a quadrilateral is obtained by the sum of two triangles with a common vertex, as shown in figure 3. Since the value of this parameter clearly depends on the hand size, the trajectories have been normalised to the subject’s hand size, obtained as the initial hand surface area in resting position.

![Figure 3. Hand’s surface area definition. A quadrilateral is obtained by the sum of the yellow triangle - defined by thumb, index and hand markers - and the light blue one - defined by index finger, little finger and hand markers.](image-url)
3. Results

In Section 2.4 we have presented the overall set of parameters that can be obtained from the test. As preliminary examples, we focus on two of them: elbow’s range of motion and hand’s area variability during the cycle task as shown in figure 4. These two cycle histories are useful to understand where the movement is compromised. Through elbow’s joint analysis, figure 4a, it is evident that both left and right limbs are over-flexed during task cycle. This could suggest problems in proximal side of the upper limb, possibly in the shoulder, that cannot flex and support the arm in the gesture in a physiological way. On the other hand, in figure 4b, it’s possible to analyze the hand area of another patient during a cycle. In this case also both sides present difficulties in managing hand aperture, but in particular the injured left side presents not only low area levels but also a different evolution during the cycle, suggesting distal problems in the limb.

Figure 4. Elbow range of motion (a) and hand’s area (b) during the task cycle. Patient’s right arm (green) and injured left arm (red). Normality range (grey) and mean (black).

In addition to the detailed cycle analysis, as presented before, it is possible to evaluate cycle overall parameters. Let’s consider as an example spatial temporal parameters expressed as a fraction of the cycle, as shown in figure 5. As before, these parameters allow to define if the stroke compromise mostly proximal or distal segment and quantify the quality of gesture of drinking. Yet this is not an exhaustive set since new parameters can be imagined as the experimentation proceeds.

Figure 5. Cycle subdivision in phases and their relative percentage. Healthy arm (green), injured arm (red) of an injured subject and normality (grey).
4. Conclusions
A novel approach to upper limbs biomechanical objective evaluation is proposed. The method is promising for the evaluation of patients with after stroke injured upper limb or with upper limbs orthopaedic problems. The protocol is based on a sequence of tasks that incorporates all major joints of the upper limb and simulates a functional task that is feasible yet challenging enough to reveal key motor deficits in individuals with movement disorders. We have chosen this daily life gesture to obtain as much motivation as possible from the subject and to focus the rehabilitation on the recovery of subject’s daily life autonomy. The information available from the proposed biomechanical model applied to the experimental protocol is huge and a set of possible evaluation parameters is presented in the paper. Preliminary results on healthy subjects and patients are promising and enable the localisation of the biomechanical problem is specific regions, where the rehabilitation will be focused. Application to a larger set of subjects and patients is going on in collaboration with the rehabilitation unit at La Colletta Hospital. It would be interesting to use this method in order to support upper limb treatment, e.g. botulinum toxin injections, constraint-induced movement therapy, and corrective surgery. The drinking cycle can offer effective and standardized quantitative evaluation pre- and post-intervention. In addition, these quantitative measures of upper limb functions may help delineate diagnoses of different movement disorders, and thus, may be important in determining structure–function relationships between brain and motor abnormalities.

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