Upper limb assessment in tetraplegia: clinical, functional and kinematic correlations
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The aim of this study was to correlate clinical and functional evaluations with kinematic variables of upper limb reach-to-grasp movement in patients with tetraplegia. Twenty chronic patients were selected to perform reach-to-grasp kinematic assessment using a target placed at a distance equal to the arm's length. Kinematic variables (hand peak velocity, movement time, percent time-to-maximal velocity, index of curvature, number of peaks, and joint range of motion) were correlated to clinical (Standard Neurological Classification of Spinal Cord Injury-American Spinal Injury Association) and functional [Functional Independence Measure (FIM) and Spinal Cord Independence Measure II (SCIM II)] evaluation scores. Twenty control participants were also selected to obtain normal reference parameters. There was a positive correlation between total motor index and FIM ($r = 0.6089; P = 0.0044$) and SCIM II ($r = 0.5229; P = 0.018$). Both functional scores showed positive correlation with each other ($r = 0.8283; P < 0.0001$). A correlation was also observed between the right and left motor indices, the motor FIM, and the SCIM II in most of the reach-to-grasp kinematic variables studied (hand peak velocity, movement time, index of curvature, and number of peaks). In contrast, for the joint range of motion (shoulder, elbow, and wrist), only the wrist in the horizontal plane showed correlation with clinical variables. This study shows that muscle strength assessed by the American Spinal Injury Association motor index influences the reach-to-grasp kinematic variables of patients with tetraplegia. However, the functional assessments did not present the same influence.

Ziel der vorliegenden Studie war die Ermittlung der Korrelation klinischer und funktionaler Evaluierungen unter Zuhilfenahme kinematischer Variablen der Greiffunktion der oberen Extremitäten bei tetraplegisch gelähmten Patienten. Insgesamt 20 chronisch erkrankten Patienten wurden zur kinematischen Untersuchung der Greiffunktionen mit Hilfe eines Objekts ausgewählt, das in einem Abstand platziert wurde, der der Armlänge entspricht. Kinematische Variablen (maximale Handgeschwindigkeit, Bewegungszeit, Prozentsatz der Zeit zur maximalen Geschwindigkeit, Index der Krümmung, Zahl der Peaks und Gelenk-Bewegungsamplitude) wurden mit den klinischen Evaluierungscores (Standard Neurological Classification of Spinal Cord Injury - American Spinal Injury Association) und funktionalen Evaluierungscores [Funktionaler Selbständigkeitsindex (FIM) und Spinal Cord Independence Measure II (SCIM II)] korreliert. Zuwanzig Kontrollteilnehmer wurden auch zum Erhalt normaler Referenzparameter ausgewählt. Es bestand eine positive Korrelation zwischen dem totalen Motorikindex und FIM ($r = 0.6089; P = 0.0044$) und SCIM II ($r = 0.5229; P = 0.018$). Beide Funktionsscores wiesen eine positive Korrelation zueinander auf ($r = 0.8283; P < 0.0001$). Eine Korrelation wurde zwischen den rechten und linken Motorikindizes, dem Motorik-FIM und dem SCIM II in den meisten untersuchten kinematischen Variablen der Greiffunktion (maximale Handgeschwindigkeit, Bewegungszeit, Index der Krümmung und Zahl der Peaks) beobachtet. Demgegenüber wies nur das Handgelenk in der Gelenk-Bewegungsamplitude (Schulter, Ellbogen und Handgelenk) in der horizontalen Ebene eine Korrelation mit klinischen Variablen auf. Die Studie verdeutlichte, dass die vom Motorikindex der American Spinal Injury Association beurteilte Muskelstärke die kinematischen Variablen der Greiffunktion von tetraplegischen Patienten beeinflusst. Die funktionalen Beurteilungen wiesen jedoch nicht den gleichen Einfluss auf.

El objetivo de este estudio fue determinar las correlaciones entre los resultados de valoraciones clínicas y funcionales y los de las variables cinemáticas en cuanto al movimiento de extensión para agarrar de las extremidades superiores en pacientes con tetraplejía. Se seleccionaron 20 pacientes crónicos para realizar una exploración cinematográfica del movimiento de extensión para agarrar, utilizando un objeto colocado a una distancia igual a la longitud del brazo del paciente. Se determinaron las correlaciones entre las variables cinemáticas (velocidad máxima de la mano, tiempo de duración del movimiento, porcentaje del tiempo que tomo alcanzar la velocidad máxima, índice de curvatura, número de valores máximos, y arco de movimiento articular) y las variables clínicas (Standard Neurological Classification of Spinal Cord Injury - American Spinal Injury Association) y las variables funcionales [Medida de la Independencia Funcional (MIF) y Medida de la Independencia en Pacientes con Afecciones de la Médula Espinal II (MIF-ME II)]. Se seleccionaron, además, 20 personas no afectadas como grupo de referencia, con el objetivo de determinar los parámetros de referencia que se utilizarían en el estudio. Se halló una correlación positiva entre el índice global de la función motora, los valores de la MIF ($r = 0.6089; P = 0.0044$) y los valores de la MIF-ME II ($r = 0.5229; P = 0.018$). Ambos resultados funcionales mostraron una correlación positiva.
Introduction
Tetraplegia represents more than 50% of all spinal cord injuries (SCI) (National Spinal Cord Injury Statistical Center (NSCIS), 2001) and causes major impact in functional independence owing to arm and hand impairments (Snoek et al., 2004).

Several treatment approaches can be applied to minimize the negative effects caused by injuries in the functional independence of individuals, such as functional electrical stimulation administration for upper limb rehabilitation movement (Wilkenfeld et al., 2006; Kilgore et al., 2008; Spooren et al., 2009). To measure the effectiveness of such techniques, clinical and functional scales are administered before and after a treatment program to identify motor and functional recovery (Van Tuijl et al., 2002).

The evaluation of key muscle groups is important to identify the motor level and to monitor patients with tetraplegia improvements [as defined by the American Spinal Injury Association (ASIA)] (Marino, 2005). Two of the most used functional evaluations for patients with tetraplegia are the Functional Independence Measure (FIM) (Van Tuijl et al., 2002) and the Spinal Cord Independence Measure II (SCIM II) (Itzkovich et al., 2002). These tests are validated and reliable, and show strong correlation with each other (Catz et al., 1997; Van Tuijl et al., 2002; Beninato et al., 2004).

However, only functional and clinical assessments are not enough to assess motor strategies used during movements. The kinematic study can produce accurate and objective information about motor strategies associated with goal-oriented tasks, and monitor administration of therapeutic techniques for the upper limb (Chang et al., 2005; Murphy et al., 2006; Wagner et al., 2008). Some studies have shown the characteristics of reach-to-grasp and pointing movements in patients with tetraplegia.
There are few studies that correlate kinematic variables with clinical measures in individuals with central nervous system injury (Chang et al., 2005; Tao and Mirbagheri, 2007). Thus, the objective of this present study was to analyze the correlation between clinical and functional assessments and kinematic variables of upper limb reach-to-grasp movement in patients with tetraplegia.

Materials and methods
Participants
Twenty chronic patients with tetraplegia, ranging from C5 to C7, of both sexes (four women and 16 men), and with a mean age of 30.5 ± 6.5 years (Table 1), were recruited from the University Hospital Outpatient SCI Rehabilitation Clinic to participate in the study. Twenty control participants (CP) of both sexes (five women and 15 men) with a mean age of 27.2 ± 3.79 years were recruited. The participants did not have any musculoskeletal limitations in the shoulder, elbow, or wrist that could interfere in the upper limb functional ability.

The participants were fully informed about the nature and possible risks of the investigation before they gave signed consent to participate in the study, which was approved by the Research Ethics Committee of the University of Campinas (No 595/2005).

Assessment
Neurological examinations of all the patients were performed according to the ASIA standards (Marino and Graves, 2004; Marino, 2005). The right and left motor indices were determined from the sum of the muscle strength of C5 and T1 segments from right and left extremities, respectively. For each motor index, scores ranged from 0 to 25. The total motor index is the sum of both arms scores (lowest score 0 and highest score 50).

The function was assessed using two scales, described below. FIM, that consists of 18 items organized in six categories, four corresponding to motor functions (self care items, sphincter control, mobility items, and locomotion) and two corresponding to cognitive functions (communication, psychosocial, and cognitive). The lowest and highest scores of the total and motor subsection ranged from 18 to 126 and 13 to 91, respectively (Van Tuijl et al., 2002).

The second scale was the SCIM II that has 16 items divided into 3 functional areas: self-care, respiration and sphincter management, and mobility. Total score can vary from 0 (minimal) to 100 (maximal) (Catz et al., 1997; Itzkovich et al., 2002).

Kinematic procedures
For the kinematic capture process, patients with tetraplegia and CP were seated in front of a task-table and instructed to reach and grasp a cone (0.11 m high, 0.03 m of superior border diameter, and 0.04 m of inferior border) that was placed in a target marked on the table, with one arm at a time. The target was positioned in front of the patient’s sternum, with a distance equal to the arm’s length (from the medial border of axilla to the distal wrist crest).

Table 1  Clinical characteristics

<table>
<thead>
<tr>
<th>Patients with tetraplegia</th>
<th>Etiology</th>
<th>Handed</th>
<th>Injury time (years)</th>
<th>ASIA</th>
<th>Motor level R/L</th>
<th>R</th>
<th>L</th>
<th>Total</th>
<th>FIM total</th>
<th>FIM motor</th>
<th>SCIM II</th>
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<td>L</td>
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<td>C5/C6</td>
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<td>R</td>
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<td>C5A</td>
<td>C8</td>
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<td>37</td>
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<tr>
<td>19^</td>
<td>F</td>
<td>R</td>
<td>13</td>
<td>C5A</td>
<td>C7</td>
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<tr>
<td>20^</td>
<td>DSW</td>
<td>R</td>
<td>12.4</td>
<td>C5A</td>
<td>C8</td>
<td>8</td>
<td>8</td>
<td>16</td>
<td>59</td>
<td>24</td>
<td>30</td>
</tr>
</tbody>
</table>

Mean/SD 12.3/3.7 12.1/2.9 24.4/6.4 69.7/15.4 34.6/15.1 34.1/8.7

ASIA, American Spinal Injury Association; CA, car accident; DSW, diving in shallow water; F, firearm; FIM, functional independence measure; L, left; R, right; SCIM II, spinal cord independence measure; SD, standard deviation.

^Made the reach-to-grasp movement on the right side.

^Made the reach-to-grasp movement on the left side.
Patients with tetraplegia were sitting in their own wheelchair and CP sat on an ordinary chair with backrest and had 90–100° of hip flexion. They were seated in front of a task-table with one target (central). The participants were asked to perform five movement repetitions to the target, first with the right arm, followed by the left arm, in a total of 10 repetitions. Participants were not allowed to practice earlier.

For the initial position, the evaluated arm was held at the side of the trunk, with the elbow at 90° of flexion and the forearm in neutral position over the table. The trunk had no restriction for anterior shifting, and the other arm, not in movement, was fixed to the abdomen, in an attempt to minimize the influence of the nonevaluated member on postural control. All participants were capable of reaching and grasping the object during the tests. From the beginning to the end of the experiment, the participants could not touch the table with the forearm. The command used to start the capture was ‘GO’, and they were instructed to perform the movement naturally and not to worry about the velocity and time duration.

Kinematic assessment data were recorded at 240 Hz by four infrared cameras (Qualisys System Medical AB-2.57, Gothenburg, Västs, Götaland, Sweden) and six reflective markers (0.015 m of diameter) (Fig. 1), being digitally low-pass filtered at 6 Hz (finite impulse response) using Matlab (The Mathworks, Inc, Natick, Massachusetts, USA). Markers 1 and 2 varied according to the upper extremity analyzed. Marker 1 was located on the contralateral acromion of the evaluated extremity and marker 2 was located on the ipsilateral acromion.

To characterize the reach-to-grasp movement kinematics, the maximal peak velocity of the reach-to-grasp was computed from the velocity vector expressed by a numerical difference from radial styloid process to xiphoid process markers in all three-dimensional planes (XYZ). Movement onsets and offsets were defined as the time at which the velocity rose above and fell below 5% of the maximal peak velocity. The percentage of time elapsed until the maximal peak velocity was achieved (percent time-to-maximal velocity).

The index of curvature (reach path ratio) shows the straightness of the wrist trajectory from the initial position to the target (Wagner et al., 2008). Five percent of the maximal peak velocity was chosen as the threshold for the characterization of a unit peak, thus yielding the overall number of peaks.

The angles of the shoulder, elbow, and wrist were determined by markers [sagittal (YZ) and horizontal (XY) planes]. The movement variables, shoulder, and elbow angles, were calculated according to Michaelsen and Levin (2004). A vector from markers 4 to 5 and from 5 to 6 was used to define wrist flexion and extension in sagittal and horizontal planes. Wrist neutral position was defined at 0°.

**Data analysis**

The Spearman correlation coefficient was used to correlate kinematic variables (hand peak velocity, movement time, percent time-to-maximal velocity, number of peaks, index of curvature, and shoulder, elbow and wrist range of motion) with clinical and functional variables. A significance level of $P < 0.05$ was used. The total motor index was used to correlate clinical variables to functional variables, however, the correlation between clinical and functional variables with kinematic variables were done separately, first with the right upper extremity and then with the left upper extremity. The correlation coefficient was interpreted according to Munro (2004): 0.00–0.25: small or no correlation; 0.26–0.49: low correlation; 0.50–0.69: moderate correlation; 0.70–0.89: high correlation.

**Table 2** Average values of kinematic variables of control participants and patients with tetraplegia

<table>
<thead>
<tr>
<th>Arm studied</th>
<th>Right ($n=19$)</th>
<th>Left ($n=19$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>CP</td>
<td>CP</td>
</tr>
<tr>
<td>Hand velocity peak (m/s)</td>
<td>0.880/0.138</td>
<td>0.789/0.135</td>
</tr>
<tr>
<td>Movement time (s)</td>
<td>0.92/0.16</td>
<td>1.53/0.08*</td>
</tr>
<tr>
<td>Percent time-to-maximal velocity (%)</td>
<td>39.1/4.3</td>
<td>25.3/4.7*</td>
</tr>
<tr>
<td>Index of curvature</td>
<td>1.31/0.10</td>
<td>1.72/0.23*</td>
</tr>
<tr>
<td>Number of peak</td>
<td>1.57/0.4</td>
<td>8.05/3.9*</td>
</tr>
</tbody>
</table>

CP, control participants; SD, standard deviation.

*Statistically significant difference between the kinematic variables of patients with tetraplegia and CP ($P<0.0001$).
correlation; 0.90–1.00: very high correlation. To compare the mean values of the kinematic variables of patients with tetraplegia and CP, the nonparametric Mann–Whitney test was used.

Results
Twenty CP and twenty patients with tetraplegia participated in the study. Patient characteristics and mean values of FIM motor index and SCIM II are shown in Table 1. There was a significant difference between the patients with tetraplegia group and CP group for the kinematic variables of movement time, percent time-to-maximal velocity, index of curvature, number of peak for both extremities (Table 2 and Fig. 2), and wrist range of motion (Fig. 3). There was no statistic difference in hand peak velocity of wrist and in the shoulder and elbow range of motion. Left and right extremities showed similarities in all kinematic variables.

Fig. 2

Velocity graph. (a) Control participants and (b) patients with tetraplegia. Kinematic variables: HVP, hand velocity peak; MT, movement time; PTMV, percent time-to-maximal velocity.

Fig. 3

Range of motion of shoulder joint, elbow, and wrist in sagittal and horizontal planes during the reach-to-grasp movement. Significant difference between patients with tetraplegia and control participants ($P<0.01$).
Table 3 Correlation between clinical variables and right and left upper limb kinematic variables

<table>
<thead>
<tr>
<th></th>
<th>Right motor index (n = 19)</th>
<th>Left motor index (n = 19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand velocity peak</td>
<td>−0.0009</td>
<td>0.2708</td>
</tr>
<tr>
<td>Movement time</td>
<td>−0.5164**</td>
<td>−0.3595</td>
</tr>
<tr>
<td>Percent time-to-maximal velocity</td>
<td>0.0816</td>
<td>0.4661</td>
</tr>
<tr>
<td>Flexion extension of the wrist (XY)</td>
<td>−0.8247*</td>
<td>−0.6614*</td>
</tr>
<tr>
<td>Flexion extension of the wrist (YZ)</td>
<td>−0.5546**</td>
<td>−0.5353**</td>
</tr>
<tr>
<td>Index of curvature</td>
<td>−0.7214*</td>
<td>−0.6596*</td>
</tr>
<tr>
<td>Number of peak</td>
<td>−0.7742*</td>
<td>−0.8295*</td>
</tr>
</tbody>
</table>

Statistical significance: *P < 0.01; **P < 0.05.

A moderate positive correlation between the total motor index and the FIM motor (r = 0.6089, P = 0.0044) and SCIM II (r = 0.5229, P = 0.018) was found. For the functional scores, there was a positive high correlation between motor FIM and SCIM II (r = 0.8283, P < 0.0001).

The right motor index showed a negative correlation with movement time, wrist range of motion, index of curvature, and number of peaks performed during reach-to-grasp movement with the right upper extremities (Table 3). The motor FIM did not present any correlation with the right kinematic variables; however, the SCIM II showed moderate negative correlation with the right index of curvature (r_s = −0.5007, P = 0.0289).

For the left upper extremities, a moderate negative correlation was found between the left motor index and the wrist range of motion, index of curvature, and numbers of peaks (Table 3). The motor FIM showed moderate positive correlation with the percent time-to-maximal velocity (r = 0.5761, P = 0.0098) for the movement of the left upper extremities. The index of curvature and number of peak correlated negatively with the motor FIM (r_s = −0.5708, P = 0.0107; r_s = −0.7439; P = 0.0003, respectively) and with the SCIM II (r_s = −0.5373, P = 0.0176; r_s = −0.6362, P = 0.0034).

The shoulder and elbow range of motion, in sagittal and horizontal planes, did not show any correlations with clinical and functional scores.

Discussion

The reaching, grasping, and pointing movements of patients with tetraplegia are usually described as slow with preservation of movement smoothness and shoulder and elbow range of motion. This study findings are similar to others with respect to CP (Laffont et al., 2000; Hoffmann et al., 2006).

The kinematic results of this study corroborate with part of these findings, once the patients with tetraplegia showed trend to lower hand peak velocity and higher movement time, in addition to similar shoulder and elbow range of motion, compared with the CP. However, there was a decrease in movement smoothness (increase in number of peaks and index of curvature) and percent time-to-maximal velocity was found earlier during the movement. Those differences, considering earlier studies, could be explained by the upper limb free active movement that did not allow support and/or control of the trunk by the upper extremities or through belts. The high wrist range of motion in patients with tetraplegia was also observed by Laffont et al. (2000) and it is probably because of the need to do tenodesis during the cone grasping.

Muscle strength could be a good indicator of functional and clinical conditions of patients with tetraplegia. Some investigators, like Beninato et al. (2004) have shown the specific contribution that each muscle group has on the performance of individual motor tasks, assessed by FIM in patients with low cervical lesions.

In addition, Fujiwara et al. (1999) showed that shoulder muscle strength, in patients with tetraplegia (C6), is an important determinant of functional ability level. Thus, the motor level might be a good predictor of functional ability in individuals with SCI (Marino et al., 1998). Data from these studies show a relationship between the motor level and the functional measures.

Both functional scores used in this study (FIM and SCIM II) showed positive correlation with the total motor indices and corroborate with earlier studies that express a relationship between motor and functional levels (Beninato et al., 2004; Rudhe and Van Hedel, 2009). In agreement with Catz et al. (1997), these two functional scores also had a high positive correlation with each other.

The FIM has been used extensively in SCI patients, and it is actually recommended by ASIA for the evaluation of these patients. However, there are some limitations of the FIM regarding a subpopulation of SCI (Van Tuil et al., 2002), where the motor score is not capable to adequately discriminate the neurological level (Middleton et al., 1998). This could be explained by the fact that this is not evaluation specific for SCI while the SCIM has been developed specifically for SCI participants and it is more sensitive to changes in function during the rehabilitation of those participants (Catz et al., 2001). The relationship between motor and functional scores agrees with Middleton et al. (1998) which shows that the more caudal the neurological level, the higher the functional independence level will be, even acknowledging that other medical and nonmedical factors could influence the functional condition.

In this study, the relationship between strength and kinematic variables were studied through ASIA motor index. Correlations between left and right motor index and kinematics variables (movement time, index of...
curvature, and number of peaks), indicate that muscle function in SCI has an important role in characterizing movement of those individuals. This leads to believe that the better the strength, the better kinematic performance, and therefore, straight and more harmonious will be the movement.

The correlation between number of peaks with right and left motor index is a sign that the higher the neurologic motor level, the higher is the movement segmentation. This could be related to several factors like trunk instability in active free movement, the absence of antagonistic muscles like triceps, and the difficulty to produce prehension through tenodesis. This last one might also be responsible for the higher mobility of the wrist in patients with tetraplegia. This relation predicts that the lower the motor index, the higher the wrist range of motion.

Functional scores also showed negative correlation with some kinematic variables, especially the ones related to movement smoothness (index of curvature and number of peaks). In addition, higher scores in motor FIM and SCIM II, are related to better reach-to-grasp movement smoothness. However, these relations are mainly in the left upper limb.

After the injury, many patients with tetraplegia change the dominance of their upper limbs, emphasizing the use of the arm that can easily perform the functional tasks. We suggest that this may have occurred with the participants in this study, as before injury, most were right-handed. Moreover, this correlation may be inconclusive as there are two factors leading to this: (i) FIM does not evaluate the upper limbs alone, but the level of independence in functional activities performance and (ii) kinematic analysis was not carried in a two-hand, but in unilateral moves.

Thus, it is observed that kinematic captures involving bimanual functional tasks and/or the use of functional scores to assess upper limb separately, can improve the correlations between kinematic variables and functional measures.

However, we believe the functional instruments used in this study (FIM and SCIM II), cannot suit the wide variability and specificity of functional tasks that a patient with tetraplegia can perform. Therefore, the use of functional instruments that directly observe the patient’s performance of relevant tasks (i.e., Assessment of Motor and Process Skills), within his context, measuring his abilities and motor processes (Fisher, 2003), might be more related to the movement kinematic assessments, as both allow an unlimited number of functional tasks.

The kinematic analysis enhances clinical and functional assessments of patients with tetraplegia, the characteristics of the motor strategies used during the performance of a motor task. Therefore, during the elaboration of a therapeutic approach, the management of motor, sensory, and functional deficits along with motor strategies used by patients with tetraplegia during upper limb movements should also be emphasized.

Some important clinical aspects, such as spasticity (Tsao and Mirbagheri, 2007) and pain (Yap et al., 2003; Jensen et al., 2007) that could influence upper limb function and motor strategies, were not assessed in this study, but it should be explored in future researches.

This study shows that muscle strength assessed by ASIA motor index influences the reach-to-grasp kinematic variables of patients with tetraplegia. However, the functional assessments did not present the same influence.

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References
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