Wrist stabilisation and forearm muscle coactivation during freestyle swimming

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Abstract

The aim of this study was to evaluate the stabilisation of the wrist joint and the ad hoc wrist muscles activations during the two principal phases of the freestyle stroke. Seven male international swimmers performed a maximal semi-tethered power test. A swimming ergometer fixed on the start area of the pool was used to collect maximal power. The electromyography signal (EMG) of the right flexor carpi ulnaris (FCU) and extensor carpi ulnaris (ECU) was recorded with surface electrodes and processed using the integrated EMG (IEMG). Frontal and sagittal video views were digitised frame by frame to determine the wrist angle in the sagittal plane and the principal phases of the stroke (insweep, outsweep). Important stabilisation of the wrist and high antagonist muscle activity were observed during the insweep phase due to the great mechanical constraints. In outsweep, less stabilisation and lower antagonist activities were noted. Factors affecting coactivations in elementary movements, e.g. intensity and instability of the load, accuracy and economy of the movement were confirmed in complex aquatic movement.

Keywords: Swimming; Phases; Wrist; Stabilisation; Coactivation

1. Introduction

The swimmers propulsion is determined by the ability to generate propulsive force while reducing the resistance to forward motion. Propulsive force is mainly generated by the arms, which provide more than 85% of the total force of the crawl stroke (Hollander et al., 1988). Different authors underlined the discriminating function of the hand wrist complex in the force production (Barthels, 1979; Schleihaufl, 1979; Wood, 1979; Berger et al., 1995). Performance appeared to be more linked to hand force–time distribution than to maximal force production in regard to the great correlations observed between power output and swimming velocity or with swimming ability (Alves et al., 1994; Wirtz et al., 1999).

To generate propulsive forces, the hand pushed the masses of water backward. To push the water, the hand must be strongly linked to the flexed arm complex in order to offer a large span, which constituted a performance advantage in competitive swimming (Troup, 1999; Toussaint et al., 2000). A large propelling surface required a stabilisation of the wrist to transmit the force from the hand to the body in order to move the body forward. The masses of water pushed away acquired one part of the hand kinetic energy (Ek). Thus, one part of the mechanical work delivered by the swimmer is dissipated in moving water. To enhance the swimming efficiency, the swimmer had to reduce the loss of kinetic energy by adjusting the hand trajectory. For an optimal propulsive force, the orientation of the hand must be constantly fitted to ever-changing directions of the hand motion during the pull to provide
propulsion in a straight forward direction (Toussaint et al., 2000). Different phases of the aquatic path were determined from the change in the hand directions in the frontal plane. Troup (1999) observed higher hand forces in the middle part of the underwater arm stroke e.g. during the insweep and the outsweep phases while Toussaint et al. (2002) concluded to higher mechanical constraints in these both phases. The constraints resulted from the backward movement of the upper arm against the water drag. Other authors observed greater muscular recruitments during these two phases (Rouard et al., 1992; Rouard and Clarys, 1995). Although most of the recently EMG studies concerned the shoulder and trunk muscles in regard to the high constraints of the shoulder joint and the possible injuries (Clarys and Rouard, 1996; Pink and Tibone, 2000), few studies concerned the forearm muscles. Results underlined the high activation either for the extensor carpi ulnaris (ECU) (Vaday and Nemessuri, 1971) or for the flexor carpi ulnaris (FCU) (Clarys, 1983).

Although Richardson (1986) suggested that the most forward propulsion was related to the ability to maintain a given hand angle during the swimming stroke which was directly affected by the ability of the forearm muscles to maintain this position, no study has investigated the wrist fixity and the associated activation of the wrist stabiliser muscles.

In on-land postural balance, Nashner (1976) observed that the force transmission was generated by means of a rigid block. Moreover, Cholewicki and McGill (1996) observed that coactivation of trunk muscles allowed transmitting forces from the upper body to the lower body during the performance of everyday activities. Many authors underlined that the rigidity required the stiffness of the involved joints. For example, Milner (2002) showed that subjects stiffened the entire arm to maintain stability of the hand against a mechanical instability of the wrist in a known direction. Furthermore, he concluded that the increase in stiffness resulted from coactivation of most of the arm muscles (Milner, 2002). In a single-joint study with unstable loads, De Serres and Milner (1991), Milner et al. (1995) and Milner (2002) found that the ECU and FCU cocontractions increased the mechanical stability of the hand by increasing the stiffness of the wrist joint. Other authors showed that antagonist coactivation counteracted the joint displacements, thereby providing stability during monocular movements of the upper limb and knee (Yamasaki et al., 2003; Kellis et al., 2003; Beltman et al., 2003).

In regard to these previous results on elementary movements and to the missing link related to the wrist stabilisation in swimming, the aim of this study was to evaluate the wrist fixation and the ad hoc recruitments of the forearm muscles during the two principal propulsive phases of front crawl stroke, e.g. the insweep and the outsweep, on well trained male subjects. It was hypothesised that the wrist was strongly fixed during these two phases as a result of specific muscular coactivation of forearm muscles like in elementary movements.

2. Methods

2.1. Subjects

An attempt was made to select a homogeneous population for the project. Seven male international swimmers participated in this study. All were medallists or finalists at the European championships (2002) with an average performance over a 100 m swim of 1.92 ± 0.09 ms⁻¹. Their age was 22.6 ± 2.7 years and height 191 ± 4 cm and weight 82.7 ± 5.3 kg.

2.2. Testing procedures

The swim test took place in a 25 m swimming pool. After a standard warm-up (1200 m swim), the subjects performed a 5 s full tethered swim to obtain maximal propulsive force ($F_{max}$P) (Fomitchenko, 1999). Following the $F_{max}$P test, the subjects realised a 25 m power maximal test (P-test) in semi-tethered swimming at maximal velocity with an added resistance of 5% of $F_{max}$P. This test was chosen to evaluate the power production according to Sharp et al. (1983) who concluded that swimming is a power-limited performance.

2.3. Data collection

The swimmer was linked to a powder brake (Lenz) by means of a belt, a rope and two pulleys. The brake exerted a constant horizontal resistive force on the swimmer. The force generated against the brake by the swimmer and the instantaneous velocity were recorded on a PC computer using Labview software. The system was fixed on the block of the start area of the swimming pool (Fig. 4) (Rouard et al., 2001).

This ergometer allowed to collect $F_{max}$P during the full tethered swimming and to measure force ($f$), velocity ($v$) and maximal power ($P$) in semi-tethered swimming.

An EMG system (ME 3000 P8, Mega Electronics Ltd., Finland) was used to record the electrical activity of two right wrist muscles: the $M. flexor carpi ulnaris$ (FCU) and the $M. extensor carpi ulnaris$ (ECU). These two muscles were chosen according to their main function in the wrist stabilisation in elementary movements (Milner, 2002). In reference to the backward direction of the hand motion, FCU and ECU were considered respectively as the agonist and antagonist muscles. The skin was shaved and rubbed with an alcohol solution. Silver/silver chloride surface electrodes with preamplifiers (Blue sensor type M-00-S, 7 mm, Medicotest, Oelstykke, Denmark) were placed in a bipolar configuration with 1.5 cm interelectrodes distance, in line with the muscle’s fibre orientation (Basmajian, 1973). Electrodes were placed in the midpoint of the contracted muscle belly as suggested by Clarys and Cabri (1993). They were covered with an adhesive bandage (Teycaderm) to avoid contact with water (Rouard and Clarys, 1995). A reference electrode was attached to a body area remote from
the studied muscles. The total gain of the amplifier was set at 1000 with a common mode rejection ratio of 92 dB and high and low passes filters respectively of 8 and 500 Hz. The EMG signals were stored on-line on an acquisition card (Flash memory 32 MB) with a sampling frequency of 1000 Hz.

Two synchronised digital video cameras (Panasonic WV-CP454E) were used to record frontal and sagittal views of the aquatic part of the arm strokes during the power test in semi-tethered swimming. The cameras were protected by a waterproof box fixed at a depth of 0.60 m. Exposure time was set at 1/250th s due to the poor lighting conditions. The 25 Hz frame rate was sufficient in regard to the average stroke frequency of 0.95 Hz reported in the literature (Craig et al., 1985). At the beginning of the experiment, a reference object was filmed in the middle part of the camera field.

To synchronise EMG and video, an electronic flashlight signal was marked simultaneously on the video and EMG recordings.

2.4. Data treatment

Force, velocity and power were calculated over a 5 s steady-state period in the middle part of the 25 m power test. In the same portion, the right fingertip, wrist and elbow were semi-manually digitised frame-by-frame with the Schleihauf’s software based upon direct linear transformation (DLT) (KA Vidéo, San Francisco State University Kinesiology Department, USA) validated by Monteil et al. (1996). All kinematic coordinates were smoothed using a Butterworth low-pass filter with padded end-points and a cut of frequency of 4.5 Hz determined by a residual analysis of the difference between filtered and unfiltered signals over a wide range of cut-off frequencies. From the fingertip trajectory on the \( y \) transversal axis, three characteristic points were identified according to Deschodt et al. (1996): E (the maximum external coordinate), I (the maximum internal coordinate) and Exit (hand exit). These three points delimited two phases from E to I (insweep) and from I to Exit (outsweep) (Fig. 1). These two phases were considered as the most propulsive part of the stroke (Schleihauf et al., 1983) and presented the greater neuro-muscular activations (Rouard and Clarys, 1995; Clarys and Rouard, 1996).

From the sagittal view, the wrist angle, between hand and forearm, was calculated frame-by-frame from the elbow, wrist and fingertip positions (Fig. 2).

The EMG data were processed with the MegaWin software. Raw EMG’s were rectified and averaged to obtain the full wave signals. The integration of the rectified EMG was calculated, per unit of time, for each phase to eliminate the phase duration effect (IEMG/T). The signal was partitioned in 10 ms windows to found the maximal IEMG value (IEMGmax). To normalise the results, IEMG/T was expressed as a percentage of IEMGmax (Clarys, 2000). The normalised IEMG/T (%) were calculated for FCU in the insweep (FIEMGins) and in the out-sweep (FIEMGouts), and also for ECU (EIEMGins and EIEMGouts).

2.5. Data analysis

Mean, SD and coefficient of variation of the wrist angle (\( CV_w = SD/mean \)) were calculated for each phase. \( CV_w \) was used to reflect the variability of the wrist angle. The higher \( CV_w \) was the less the wrist was fixed. Descriptive statistics were expressed as means ± SD. For each parameter, the coefficient of variation (\( CV = SD/mean (%) \)) was calculated to evaluate the dispersion of the population. Differences between insweep and out-sweep were determined
using a Wilcoxon signed rank test \((p < 0.05)\). Spearman’s correlation coefficients were applied to determine the relationships between IEMG \((\%)\) and CVw \((\%)\). The level of statistical significance was set at \(p < 0.05\).

3. Results

Mean power \((P)\) was \(68.84 \pm 1.188\) W, with a dispersed population \((CV=15.33\%)\).

CVw was very low in the insweep \((5.06 \pm 4.59\%)\) with significant increase for the outsweep \((13.82 \pm 12.37\%)\) \((p = 0.0280)\). The wrist appeared strongly fixed in the sagittal plane during the insweep and was less stable in the outsweep. See Tables 1 and 2 for individual results.

FCU presented a similar level of activation for the insweep and outsweep phases with high correlation between both \((r = 0.77)\) (Fig. 3). IEMG for ECU was greater in insweep than in outsweep \((39.30 \pm 21.15\%, \text{vs.} 17.01 \pm 10.32\%)\) with high correlation between both \((r = 0.78)\). Whatever the muscle, the population appeared strongly heterogeneous with similar CV for the ECU and the FCU in insweep \((respectively, 53.81\% \text{and} 54.48\%)\) and higher CV for the ECU than for the FCU in outsweep \((respectively, 60.68\% \text{and} 40.81\%)\). See Tables 1 and 2 for individual results.

Whatever the muscle and the phase, no significant correlation was observed between IEMG \((\%)\) and CVw \((\%)\).

4. Discussion

The aim of this study was to evaluate the stabilisation of the wrist joint and the activation of the wrist muscles during the two principal phases of freestyle stroke e.g. the insweep and the outsweep during a maximal power test.

The power results were higher than those reported by Costill et al. \((1986)\) in similar semi-tethered condition. The greater values could reflect the high expertise level of the studied swimmers since many authors concluded that sprint performance was strongly linked to power ability \((Sharp et al., 1983; Craig et al., 1985; Fomitchenko, 1999)\).

The low variations of the wrist angle \((CV_w)\) showed that the wrist appeared strongly fixed in the sagittal plane during the middle part of the underwater arm stroke. The great wrist stability corresponded to the higher mechanical constraints applied on the hand during these phases as mentioned by Troup \((1999)\). The fixity of the wrist could also correspond to the link of the hand and the forearm to form a large span, which presented a performance advantage in swimming \((Troup, 1999)\). Furthermore, the stabilisation of the wrist allowed transmitting the force from the hand to the body in order to move the body forward through the water as suggested by Richardson \((1986)\).

Results indicated lower CVw during the insweep compared to the outsweep. The greater stabilisation of the wrist in the insweep phase could be due to the magnitude of mechani-

<table>
<thead>
<tr>
<th>Inswep</th>
<th>Wrist angle (°)</th>
<th>CVw (%)</th>
<th>FIEMG (%)</th>
<th>EIMG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>183.38</td>
<td>14</td>
<td>29.68</td>
<td>28.60</td>
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<tr>
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<td>198.43</td>
<td>3</td>
<td>23.49</td>
<td>29.40</td>
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<tr>
<td>Subject 3</td>
<td>174.03</td>
<td>8</td>
<td>26.16</td>
<td>56.34</td>
</tr>
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<td>Subject 4</td>
<td>198.30</td>
<td>4</td>
<td>39.53</td>
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<td>64.16</td>
<td>36.59</td>
</tr>
<tr>
<td>Subject 6</td>
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<td>2</td>
<td>22.32</td>
<td>56.94</td>
</tr>
<tr>
<td>Subject 7</td>
<td>179.05</td>
<td>3</td>
<td>11.52</td>
<td>47.89</td>
</tr>
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</table>

<table>
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<tr>
<th>Outsweep</th>
<th>Wrist angle (°)</th>
<th>CVw (%)</th>
<th>FIEMG (%)</th>
<th>EIMG (%)</th>
</tr>
</thead>
<tbody>
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<td>176.43</td>
<td>13</td>
<td>40.95</td>
<td>13.31</td>
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<td>159.27</td>
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<td>40.03</td>
<td>25.32</td>
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<td>15.81</td>
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<tr>
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<td>168.12</td>
<td>13</td>
<td>21.89</td>
<td>25.31</td>
</tr>
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</table>
from linear to non-linear, Clarys and Rouard (1996) found the insweep presented the greater force and power of water acquired. As the subject pushed the water, the mass of water acquired $E_{\text{kin}}$ and, consequently, presented less resistance for the swimmer (Toussaint et al., 2000).

The $CV_w$ results reflected high mechanical constraints of the upper limb during these two phases which could imply particular muscular recruitments.

FIEMG was approximately 30% with similar values for insweep and outsweep phases. This level of activation corresponded to previous studies (Rouard et al., 1992; Rouard and Clarys, 1995). The hand flexion during the insweep phase was supported by the FCU and forearm flexors to stabilise the hand to push the water (Rouard and Clarys, 1995).

An important antagonist activity of the ECU (40%) was observed with higher values for the insweep than for the outsweep. This result confirmed previous studies in swimming on other antagonist muscles. Rouard and Billat (1990) observed higher reciprocal contractions of the biceps–triceps during the pull phase than during the push phase. As all past studies in swimming, these phases were determined from a model of movement, which only considered the sagittal plane. More recently according to the new 3D model of the hand movement (Schleihauf et al., 1983), Clarys and Rouard (1995) showed that the side pull-push phases corresponded approximatively to the front insweep-outsweep phases. The decrease of ECU activity from the insweep to the outsweep phase was in the same way of the decrease of the biceps–triceps reciprocal contractions from the pull to the push phase (Rouard and Billat, 1990). Studies on elementary movements showed that antagonist activity was strongly linked to the load applied on the agonist muscle. Basmajian and De Luca (1985) showed that the higher the load that the subject supported, the higher were the “reciprocal activities” of the muscles. As a result, we could suppose that the higher ECU antagonist activation during the insweep reflected the greater load applied on the hand during this phase compared to the outsweep one (Monteil, 1992). The decrease in antagonist activity with decreasing load in complex aquatic movements appeared in agreement with previous studies on movements in isometric conditions with different loads.

Milner and Cloutier (1993) showed that ECU coactivation increased during wrist movement with mechanical instability. The high resistance of the water on the hand changed along the cycle creating an unstable load on the hand. Consequently, the high ECU in swimming could also be associated to the unstable load created by the water on the hand.

Furthermore, in swimming the hand trajectory presented constant fittings in three planes inside each phase to adjust the hand trajectory to research stable mass of water and to have the more efficient position of the arm (Schleihauf, 1974). In a multi-joint pointing task, Gribble et al. (2003) concluded that the cocontraction allowed enhancing the accuracy of the movement. As a result, we can suppose that the high ECU coactivation in front crawl could correspond to the improvement of the accuracy of the continuously fitting of the hand.

On single-joint movements with an inertial load, Hasan (1986) suggested that coactivation may have served to optimise the stiffness by reducing the alterations in the central drive necessary for the performance of movement, thereby reducing the effort. Referring to the high level of performance of the studied population, we assumed that the high antagonist ECU activity allowed the swimmer to improve his wrist fixation to perform more economically. This confirmed previous studies on top level swimmers (Rouard and Billat, 1990).

To summarise, high ECU activity could be explained principally by high and unstable loads due to the water resistance, especially during the insweep phase, but also by the accuracy of the hand trajectory adjustments and by a strategy to limit the effort of the wrist fixation.

Although high stabilisation of the wrist and strong coactivations were observed, no significant correlation was obtained between IEMG(%) and $CV_w(\%)$ indicating no link between muscular activation and joint stiffness. This result indicated that stability of the wrist might not be directly related to the neuromotricity of the muscles surrounding the wrist joint. Herzog et al. (2000) concluded that the passive properties of muscle were involved in the external forces production. Furthermore, O’Connor and Hamill (2004) precised that the passive properties may lead to greater tissue loads that were not revealed by electromyography. In regard to the lack of correlations between the IEMG and the wrist stabilisation, we assume that the stability could be related to the mechanical passive properties of the involved muscles.

5. Conclusion

The aim of the study was to investigate the stabilisation of the wrist and the role of forearm muscles in a homogeneous group of top level swimmers during the two major stroke phases (insweep and outsweep) of the front crawl. Strong stabilisation of the wrist and high antagonist ECU activity were observed in the middle part of the underwater arm stroke with greater values during the insweep phase, principally due to the magnitude of water resistance. Factors affecting coactivations in elementary movements, e.g. intensity and instability of the load, accuracy and economy of the movement were confirmed. The present findings added to the understanding of the importance of the wrist and forearm complex in freestyle swimming in top level swimmers. Moreover, it will be interesting to measure the forces that acted on the hand.
to study the relationships between force and EMG, force and co-activation and force and fixation in aquatic movements. Furthermore, the results have to be completed by the study of the same parameters in non-elite swimmers to evaluate the influence of expertise level on wrist stabilisation and muscular ad hoc recruitments.

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References


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