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Research article

Technical Skills Influences on Front Crawl Tumble Turn Performance in Elite Female Swimmers

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Abstract

The objective of this research was to compare technical skills composed of kinematic and kinetic variables in the complex motor task of a tumble turn between 9 elites and 9 sub-elite female swimmers. The best tumble turn among three attempts was analyzed using a three-dimensional underwater protocol. A total of 37 kinematic variables were derived from a Direct Linear Transformation algorithm for 3D reconstruction, and 16 kinetic variables measured by a piezoelectric 3D force platform. Data were analyzed by Student's t-test and effect size statistics. Pearson correlations were applied to the data of the eighteen swimmers to relate the association of 53 kinematic, kinetic variables to the performance of the tumble-turn (3 meters Round Trip Time, 3m RTT). The approach and the whole turn times were faster for elite swimmers compared to sub elites (1.09±0.06 vs. 1.23±0.08 sec, and 2.89±0.07 vs. 3.15±0.11 sec.), as well as the horizontal speeds of the swimmers' head 1 m before the rotation (1.73±0.13 vs. 1.57±0.13 m/sec.), at the end of the push-off on force platform (2.55±0.15 vs. 2.31±0.22 m/sec.) and 3 m after the wall (2.01±0.19 vs. 1.68±0.12 m/sec.). Large differences ($|d| > 0.8$) in favor of the elite swimmers were identified for the index of upper body extension at the beginning of the push-off, the lower limb extension index at the end of push-off, and among the kinetic variables, the horizontal impulse and lateralization of the push-off. Correlations for the whole group revealed a moderate to strong relationship between 6 body extension indices and 3mRTT performance. For the kinetic variables, the correlations indicated the fastest swimmers in 3mRTT showed large lateral impulse during placement ($r=0.46$), maximum horizontal force during the push-off ($r=0.45$) and lateralization of the push-off ($r=0.44$) (all $p<0.05$). Elite female swimmers had higher approach and push-off speeds, were more streamlined through the contact, and showed a higher horizontal impulse and lateralization of the push-off, than their sub-elite counterparts.

Key words: Biomechanics, complex motor skill, swimming, 3-D analysis.

Introduction

From Rome 2021 to Rome 2022, from the European Junior Championships (47.30 sec.) to the new World Record in the 100-m freestyle (46.86-s), scientific analysis of David Popovici's 100-m race highlighted that the turn section (5 m in+15 m out) showed the largest improvement of 0.33 seconds faster than the European Juniors (Polach et al., 2022). This recent analysis confirms many scientific studies demonstrating that performance in swimming is highly linked to the turn times (Arellano et al., 1994; Blanksby et al., 1996; Cossor et al., 1999; Marinho et al., 2020; Morais et al., 2019).

In the swimming literature, multiple authors (Chollet, 1997; Counsilman, 1977; Costill et al., 1992; Maglischo, 1993) have defined the tumble turn as comprising five main phases: approach, rotation, wall contact, underwater phase, and break-out phase. Wall contact can be divided into two sub-phases: the placement is preparatory, and the second sub-phase, much more studied, is the push-off (Daniel et al., 2003; Lyttle et al., 1999; Prins and Patz, 2006). Placement begins when the feet make contact with the wall and ending with inversion of the vertical force applied on the wall (Puel et al., 2012; 2022). The end of contact with the wall marks the beginning of the underwater phase. Like the contact phase, underwater activity can be divided into two sub-phases: the glide and the underwater propulsion sub-phase (Lyttle et al., 2000). Turning is a complex motor skill and improving performance of the entire turn (ie. 3 meters Round Trip Time, 3mRTT) requires progress in each sequences of approach, rotation, push-off, glide and underwater swimming phases (Nicol et al., 2019; Puel et al., 2010; 2022).

In swimming, performance is largely determined by a combination of factors related to physical and energy potential (the power output), and technical proficiency (drag and propelling efficiency) (Havriluk, 2010; Toussaint and Beek, 1992). The importance of strength and power capabilities for the tumble turn performance several studies are evidenced by significant relationships between the power qualities deployed on the turn wall (maximum strength, power, and impulse) and performance (Blanksby et al., 1996; Jones et al., 2018; Keiner et al., 2019; Miyashita et al., 1992; Pereira et al., 2006). It is likely that the level of turn performance depends on the optimal transformation between this force deployed and the tumble-turn technical skill (Puel et al., 2012; 2022). For example, during the push-off, the horizontal force on the wall should be strong enough to create high velocity (Cossor et al., 1999), and the swimmer must simultaneously twist in a prone position and streamline to reduce drag at the time of maximum push-off (David et al., 2022; Nicol et al., 2019; Puel et al., 2012).

Technical skills associated with fast tumble-turns include greater speed maintenance when approaching the wall (Blanksby et al., 1996; Puel et al., 2012; Simbana et al., 2018), long head-wall distance when swimmers begin

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their transverse rotation (Blanksby et al., 1996), higher lateral impulse during the placement (Puel et al., 2012; 2022), optimal wall-contact times and tuck indexes (David et al., 2022), streamlined postural placement at the beginning of the contact (Puel et al., 2012) and along the push-off phase (Cossor et al., 1999; Puel et al., 2022), and a smaller decay of speed during the glide phase as a function of a streamlined position achieved at an optimal depth inducing a decrease in wave drag (Lyttle et al., 1999; Novais et al., 2012; Vennell et al., 2006).

It is likely that the strength qualities and technical skills of the turn are acquired through the specific training conducted daily throughout a swimmers' careers. (Cossor et al., 1999; David et al., 2022). However, to our knowledge there are few studies that have analyzed the effects of expertise of the swimmer in terms of technical skills composed of kinematic, and kinetic variables that underlie performance in the tumble-turn (Takahashi et al., 1983; Jones et al., 2018). However, these studies were not conducted from a holistic perspective aimed at analyzing the plurality of technical skills involved in the five phases of the tumble-turn (ie. approach, rotation, wall contact, underwater phase, and resumption of swimming). In addition, only the horizontal component of force applied to the wall has been studied so far. Three-dimensional studies have shown that lateral and vertical components are highly correlated to turn performance (Lyttle and Mason, 1997; Puel et al., 2010; 2022; Roesler, 1997; 2003).

Therefore, the aim of the study was to use an extensive protocol for 3D underwater analysis developed by Puel and collaborators (2010; 2012; 2022) to assess a relevant set of kinematic and kinetic variables composing the technical skills of the front crawl tumble turn. We sought to compare kinematic and kinetic variables between elite and sub-elite swimmers during front crawl tumble turn. Our hypothesis is that the higher level of swimming performance among expert swimmers is reflected in better turn performance. An improvement in turn performance is likely related to the interaction between technical skills variables (e.g. greater speed maintenance when approaching the wall, smaller decay of speed during the glide phase, higher forces, powers and maximum impulses on the wall, optimal wall-contact times and tuck indexes, streamlined postural placement at the beginning of the contact and along the push-off phase).

Methods

Participants

Eighteen competitive female swimmers participated in this study. Two groups with the same number of swimmers were formed according to their performance level (see main characteristics in Table 1). According to the classifications (Gonjo and Olstad, 2021), the 9 swimmers of the elite group had a performance level corresponding to a FINA point level >700 points. These swimmers were part of the French national swimming team and competed at the highest level (Beijing 2008, London 2012 Olympic Games and Roma 2009, Shanghai 2011 World Swimming Championships; whereas the 9 sub-elite female swimmers competed only in French National Championships (FINA point level < 650). Elite swimmers completed a larger weekly volume of swimming training (33,600 ± 8300 m·wk^{-1} vs. 22, 300 ± 3400 m·wk^{-1}) and dry-land training volume (109 ± 118 min·wk^{-1} vs. 54 ± 71 min·wk^{-1}) than sub-elite swimmers. All of the participants practiced the front crawl tumble turn on a regular basis and used it for competition races. Swimmers also used only the dolphin kicking technique for underwater propulsion. Adult participants and the parents of swimmers under 18 were informed in detail about the procedures and gave informed consent prior to the experimentation. The ethics committee of the University approved the investigation.

Table 1. Main physical characteristics and performance level of the two groups of female swimmers. Data are means (SD).

	Sub-elite swimmers (*n* = 9)	Elite swimmers (*n* = 9)
Age (years)	16.1 (1.1)	21.7 (4.3)
Body height (m)	1.66 (0.05)	1.75 (0.04)
Body mass (kg)	55.5 (5.8)	62.3 (4.9)
Performance (%)	85.0 (2.8)	95.9 (2.7)
Performance (FINA, pts)	585 (55)	817 (61)
Performance (200 freestyle, sec)	119.5 (2.9)	135.3 (4.2)

The performance level (L, %) is the ratio between the 200 m freestyle world record (50 m pool) and the swimmer's best performance.

Procedure

We reused an extended protocol proposed for elite male swimmers (Puel et al., 2012, 2022) to assess a larger set of performance variables. The participants were asked to perform several front crawl tumble turns as fast as possible until entire satisfaction of all the partners of the study (the swimmer herself, her coach and the researchers). This sequence was placed after the warm-up. A warm-up and a few practice turns were always done beforehand. Finally, never more than three turns were performed consecutively, without a long rest period, so that fatigue would not influence the results (Blanksby et al., 1995). Coaches timed each turn and researchers ensured that both the swimmer's feet hit the force platform mounted on the turning wall. The Sportlab software comprising five separate software programs programmed in the LABVIEW 6.1 environment automated the detection of the head passing the virtual 3m line, permitting calculation of the 3mRTT parameter, and time related to the performance at the turn.

The derivation of the horizontal position of the head allowed for obtaining the horizontal velocities, and times for the 3 m before the turn wall and 3 m after. The calculated differences in seconds between the automatic and operator detections for the times of end of push-off, end of glide, start of contact, start of rotation and resumption of swimming were 0 sec., 0 sec., -0.6 msec. [-6 : 5, 95%CI], 1.5 msec. [-0.1 : 4, 95%CI], 0.25 msec. [-0.8 : 2, 95%CI] respectively. The intraclass correlation coefficient between the automatic and manual detections was 0.99. After 3 consecutive turns (with 3 min interval between each attempt), the swimmer had to rest to prevent fatigue (Blanksby et al., 1995). Except for a few cases, the maximum number of turns performed by each swimmer did not exceed 3. Only the best-time turn of each swimmer was analyzed.

Experimental set-up

The swimmers were analyzed when passing through a parallel piped calibrated space with mean dimensions of 4.11 x 1.11 x 1.89 m for the horizontal (main movement direction), vertical (pool depth) and lateral (lane width) directions, placed in contact with the turning wall and the water surface. The calibration structure was composed of 5 to 7 air-filled vertical PVC tubes, all 0.02 m in diameter, and of equal length. Each end was marked in contrasting color to be used as a calibration point. Each tube was attached to a thin non-elastic wire, itself attached to a weight on the pool floor. Four contrasting points marked on the force platform completed the structure. The structure was completed by four contrasting points marked on the corners of the vertical force platform placed just under the water surface and measured 0.6 m high and 0.4 m wide. Thus, the calibration structure included at least 14 and at most 18 calibration points. This type of configuration is in accordance with the methods of Challis and Kerwin (1992), who preferred use of control points distributed around the outside, rather than within the space to be calibrated.

The calibration system was left in place during the passage of swimmers, leaving more time for testing, which was limited by the autonomy of mini-DV cameras and batteries. This configuration also meets the recommendations of Chen et al. (1994), who stated that a homogeneous distribution of calibration points is required, and the recommendations of Wood and Marshall (1986), who stated that the sights be located as close as possible to the site of movement, and the volume should contain the movement. Last, a similar configuration was used by Elipot et al. (2009, 2010) to study the underwater phase following the swim start.

A set of 4 to 8 stationary mini-DV stationary mini-DV video cameras (Sony DCR-HC62E and DCR-HC96E, shutter speed: 1/120 s) were located underwater at different depths in waterproof cases (Sony SPK-HCD). The 2D image coordinates were transformed to 3D object-space coordinates using the direct linear transformation algorithm (DLT) (Abdel-Aziz and Karara, 1971; Elipot et al., 2009) in Sport Lab software. Initially intended to allow 3D reconstruction from two cameras, the software was modified to allow reconstruction from two up to eight cameras. This increase in the number of cameras that can be used simultaneously increases the number of points reconstructed. Multiplication of the shots maximizes the number of reconstructed points, and refines the reconstruction of these points. Thus, during each experiment, all available cameras were used. This arrangement also made it possible to ensure the reconstruction even when various complications arose such as poor sealing (presence of water or destruction of the camera), poor quality of a mini DV tape, loss of images during digitalization, defective camera battery (incomplete recording), poor framing (the camera is not in the right place). The digitized video files initially sampled at 25 frames/second were opened in Virtual Dub software. The bob double video filter was used to oversample the interlaced videos to double the frequency (i.e. 50 frames/second, 50 hertz).

The interlacing consisted of recreating 50 numbered frames/s, alternating even and odd frames, and respecting the chronology of the video (two hundredths of a second separated each consecutive image). For a configuration with 14 test patterns and five cameras (see figure above), the average 3D position deviation calculated was 12.8 mm with a maximum deviation of 28.7 mm. The distance between the real coordinates of the calibration points and the calculated coordinates along the three axes x, y and z were 3.7 mm, 10.7 mm and 3.5 mm. In comparison with the dimensions of the calibrated space, the errors were similar to those presented by Payton et al. (2002) and Coleman and Rankin (2005); i.e., respectively 0.09, 1.11, and 0.46% (7.1, 9.8 and 5.1 mm) of the horizontal, vertical, and lateral calibrated dimensions. The angle between each pair of consecutive cameras ranged from 30 to 55° (Figure 1) with synchronization obtained using an underwater strobe flash. The temporal precision was 0.02 s. A piezoelectric 3D force platform (Kistler 9253B12, 2000 Hz) was also mounted underwater on the turning wall. Kinetic data capture was carried out by an 8-channel charge amplifier and a DAQ system with BioWare software (Kistler 9865E1Y28 and 5691A1). Kinematic and kinetic data were synchronized at the end of the push-off.

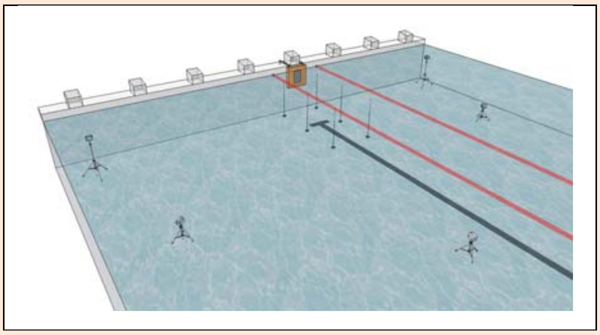

Figure 1. 3D kinematic calibration system and camera set-up. The figure shows a 5-camera configuration.

Measurements

One complete turn was analyzed for each swimmer by manual tracking of the center of the head visible during most of the movement (Costill et al., 1992). The center of the head was determined as the middle of the inter-ear segment (geometric center of the skull) (Winter, 2004). The approach began at the same time as the turn, i.e., when the swimmer's head passed the line located 3 m before the turn wall. Turning started when the swimmer's head began to submerge underwater (Blanksby et al., 1996). The software program was configured to detect this moment automatically, but manual observation remained the detection solution chosen by the majority. The end of the rollover corresponded to the beginning of the contac,t and was detected via the dynamometric signals. The approach time and the roll over time were calculated. Sixteen other anatomical points were also tracked (left and right hallux, ankles, knees, hips, shoulders, elbows, wrists, and fingertips).

Given the sagittal symmetry of the swimmer during the contact phase, a seven-segment model (feet, legs, thighs, trunk, head, arms, and forearms-hands; Winter, 2004) was used to assess the body extension indexes. For each of the segments, the distal and proximal points were respectively the tips of the hallux and the ankle; ankle and knee; knee and hip; hip and shoulder; the center of the head; elbow and shoulder; fingertips and elbow. The anatomical landmarks of the proximal points and the positions of the center of gravity of the segments relative to the proximal points are indicated in Winter (2004). The experimenters were trained in detection of the center of gravity of the segments from the videos of swimmers showing several points of view. Kinematic and kinetic data were smoothed by the Savitzky-Golay filtering method (degree of polynomials: r=2; sizes of the moving window: w_k=13, w_d=65; Savitzky and Golay, 1964), used to study underwater (Domenici et al., 2000) and human movements (Sibella et al., 2007). Speeds were computed by the same method (Staggs, 2005).

Kinematic (absolute and relative times, horizontal speeds and distances, depths, body extension indexes, Figure 2) and kinetic variables (forces, impulses, and decompositions of the push-off force vector at the horizontal force peak) were computed for each phase and the global turn performance. The time taken to swim from 3 m in to 3 m out the turning wall (3mRTT), and the approach duration (AT) were also determined. Speeds were the instantaneous horizontal speed of the swimmer's head 3 m before the turning wall (VIn), the speed 1 m before the beginning of the rotation (V1mR), the maximal horizontal speed (Vmax), the speed at the end of the contact (when glide began) (VG), and the speed 3 m after the wall (VOut). Distances were horizontal distance between the swimmer's head and the turning wall, the head-to-wall distance when swimmer's speed reduced to 2.2 m/s (D22), when swimmer's speed went down to 1.9 m/s (D19), or the head-to-wall distance at the end of the glide (when underwater propulsion began) (UD).

According to the methodology indicated in Puel et al., 2012, 2022, lower limb extension indexes were determined as the ratios between the hips-to-wall distance and the sum of foot, leg, and thigh lengths at chosen key times: the first contact, the end of placement (Lyttle et al., 1999; Prins and Patz, 2006), the force peak, and the end of push-off (respectively, CLLei (Contact Lower Limb extension index), PoLLei (Push-off Lower Limb extension index), PeLLei (Peak Lower Limb extension index), and GLLei (Glide Lower Limb extension index). Similarly, upper body extension indexes CUBei (Contact Upper Body extension index), PoUBei (Push-off Upper Body extension index), PeUBei (Peak Upper Body extension index), GUBei (Glide Upper Body extension index) were computed as the ratio between the fingers-to-hips distance and the sum of trunk, arm, forearm, and hand lengths respectively. The lower limb extension index was derived as the ratio of the horizontal distance from the hips to the wall to the sum of the segmental lengths of the feet, legs and thighs (Puel et al., 2022). The larger the ratio, the more extended the swimmers' lower limbs were. Conversely, the smaller the ratio, the more the feet, legs and thighs were flexed. The upper body extension index was computed as the ratio of the horizontal distance between the fingers and hips to the sum of the segmental lengths of the trunk, arms and forearms and hands (Puel et al., 2022). The greater the ratio, the more extended the swimmers' upper limbs were. Conversely, the smaller the ratio, the more the hands, forearms and arms were bent.

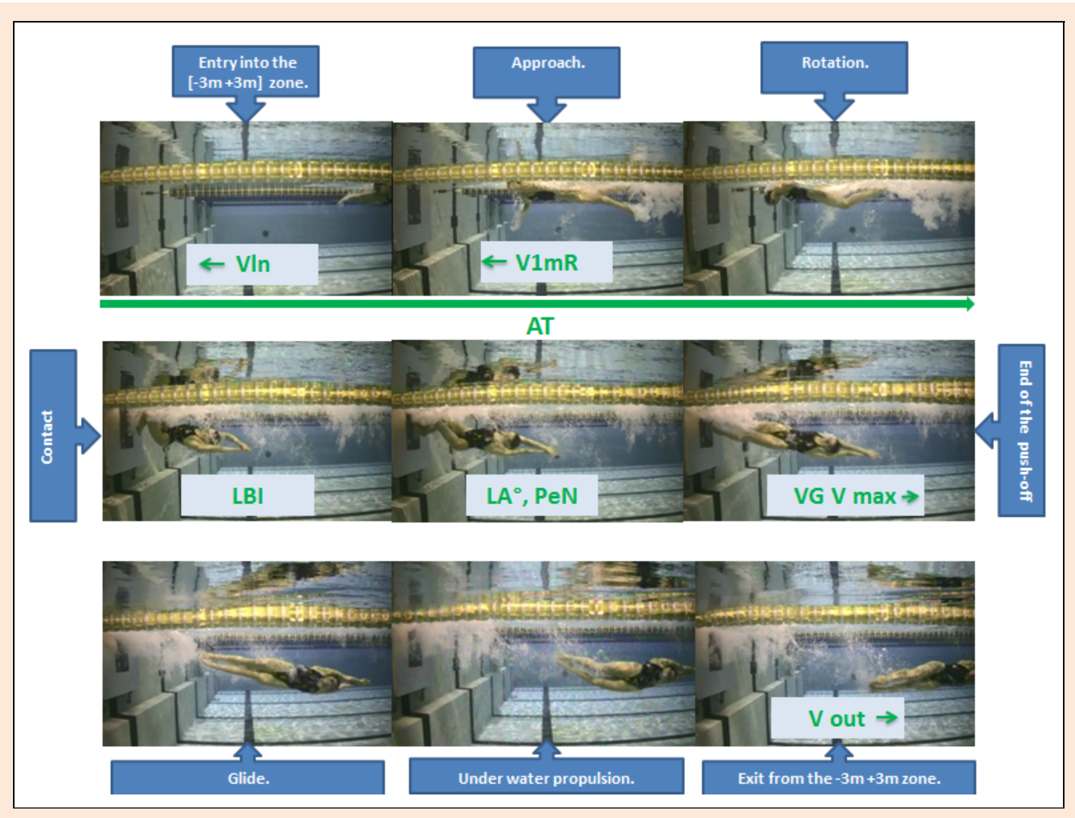

Figure 2. Selected kinematical variables for a European champion swimmer in the 800 m freestyle. Each variable's acronym was clearly defined in the Methods section and in the Table 2.

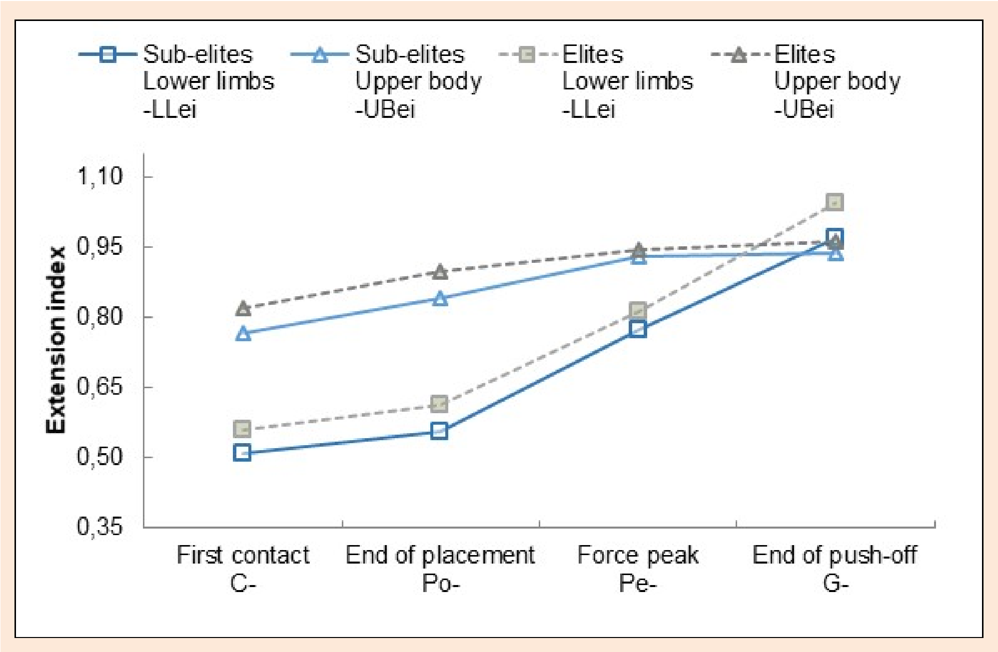

Figure 3. Lower limbs (squares) and upper body (triangles) extension indexes at 4 chosen key times (first contact, end of placement, force peak, and end of push-off) for sub-elite (blue/continuous line) and elite female swimmers (gray/dashed line).

For kinetic variables the maximal value of the horizontal component of the force during the push-off (the force peak) (Pe) was determined and normalized by the swimmer's body weight (nPE). Five impulse variables were computed for the three components of force (lateral, vertical, and horizontal, orientations in accordance to the calibrated space dimensions) and during chosen phases (placement, from the push-off beginning to the force peak, and during the whole push-off). The lateral impulse during the placement (i.e. the integration of the lateral component of the force applied by each swimmer on the turning wall between the first contact and the beginning of the push-off sub-phase, LBI), the lateral impulse during the push-off (LPoL, N.s), the vertical impulse during the push-off (VPoL, N.s), the horizontal impulse during the push-off (HPoL, N.s) and the horizontal impulse to the force peak (HPeIP, N.s) were determined. Finally, the vertical and lateral angles of the force vector at the horizontal peak were also computed (VA°, LA°) (Figure 3).

Statistical analysis

All variables were compared between the two groups using a Student *t* test for independent samples. The normality of both samples was verified by the Shapiro-Wilk test. In the case of non-normal distributions, which occurred for only 2 of the 56 variables studied, the non-parametric Mann-Whitney test for independent samples was used. Effect sizes (*d*) were also computed to complement and classify the magnitude of the differences between samples (Cohen, 1988; Nakagawa and Cuthill, 2007) where $\leq |d| \leq 0.5$ was deemed small, $0.5 \leq |d| \leq 0.8$, |moderate, and d| > 0.8 large. (Cohen, 1988). Differences in results were deemed statistically significant when $p \leq$ at 0.05. Finally, for the group considered as a whole, Pearson correlation coefficients were calculated between technical skills (composed of all kinematic and kinetic variables) and 3mRTT turning performance. The magnitude of the correlations was interpreted with reference to Taylor (1990) with correlations ≤ 0.35 considered low, between 0.36 and 0.67 modest, and between 0.68 and 1 strong.

Results

Substantial differences were identified between the elite and sub-elite swimmers for 8 kinematic variables: the approach and the whole turn times (respectively, AT and 3mRTT), the head-to-wall distance when the speed goes to 2.2 m/s (D22), and the horizontal speeds of the swimmers' head 3 m before the turning wall (VIn), 1 m before the rotation (V1mR), at the end of the push-off (VG), 3 m after the wall (VOut), and the maximal speed (Vmax). Large differences ($|d| > 0.8$) were identified for 3 more kinematic variables: the head-to-wall distances at the end of the glide (when swimmers began underwater propulsion), when the swimmer's speed exceeds 2.2 m/s (respectively, UD and D22), and the lower limb extension index at the end of push-off (GLLei). Times were shorter for elite swimmers whereas distances, speeds and extension indexes were higher. These differences are detailed in Table 2.

Among the kinetic variables only the horizontal push-off impulse (HPoL, N.s) and lateralization of push-off (LA, °) was higher in expert swimmers. For the other kinetic variables, the differences between the two groups were small to medium ($0.01 \leq |d| \leq 0.50$) and largely non-significant (p>0.10). For the group as a whole, large correlations highlighted the links between fast approach, glide and underwater speeds and 3mRTT performance: AT the duration of the approach, calculated as the time between the moment when the head crosses the 3-m line and the moment or head of the swimmer begins to sink underwater (s) (r=0.89), T-out the time between contact and +3m (s) (r=0.91), and V1mR the horizontal velocity of the head 1m before the approach-return limit (m/s) (r=0.91) (all, p<0.01).

Correlation analysis also revealed a moderate to strong relationship between body extension and 3mRTT performance (actual extension to theoretical maximum possible extension (ΔUBL, m) (r=-0.56), horizontal hip-to-wall distance at the start of contact (CHD, m) (r=-0.53), horizontal hip-to-wall distance at the start of push (PoHD, m) (r=-0.51), horizontal hip-to-wall distance at the end of push-off (GHD, m) (r=-0.45), horizontal finger-to-hip distance at the start of contact (CDD, m) (r=-0.48), and horizontal finger-to-hip distance at the start of push (PoDD, m) (r=-0.47) ($p<0.05$ for all variables) indicating that the higher the value of these variables the smaller the 3mRTT in time and therefore the faster the speed. For the kinetic variables, the fastest swimmers in 3mRTT showed large evident lateral impulse during placement (LBI, N.s, r=-0.46, $p<0.05$), maximum horizontal force during the push-off (Pe, N, r=-0.45, $p<0.05$) and lateralization of the push-off (LA, °, r=0.44, $p<0.05$).

Table 2. Analysis of performance variables of the front crawl tumble turn according to skill level. Data are means (SD).

	Sub-elite swimmers (*n* = 9)	Elite swimmers (*n* = 9)	IC (95%)	Effect size (*d*)	p-value
Turn time (3mRTT, s)	3.15 (0.11)	2.89 (0.07)	(-0.35:-0.18)	3.05	0.000
Maximal speed (Vmax, m/s)	2.34 (0.22)	2.58 (0.17)	(0.05:0.43)	-1.03	0.015
Speed 3 m before the wall (VIn, m/s)	1.54 (0.22)	1.75 (0.23)	(-0.42:0.01)	1.06	0.057
Approach time (AT, s)	1.23 (0.08)	1.09 (0.06)	(-0.20:-0.06)	1.88	0.001
Speed 1 m before the rotation (V1mR, m/s)	1.57 (0.13)	1.73 (0.13)	(-0.28:-0.04)	1.70	0.013
Speed at the end of push-off (VG, m/s)	2.31 (0.22)	2.55 (0.15)	(0.21:0.68)	-1.06	0.011
Head-wall distance when speed goes to 2.2 m/s (D22, m)	1.86 (0.16)	2.31 (0.32)	(0.18:0.48)	-1.59	0.001
Speed 3 m after the turning wall (VOut, m/s)	1.68 (0.12)	2.01 (0.19)	(0.18:0.48)	-2.05	0.000
Lower limb extension index at the end of push-off (GLLei)	0.97 (0.07)	1.04 (0.07)	(-0.01:0.48)	-0.83	0.079
Upper body extension index at beginning of push-off (PoUBei)	0.85 (0.07)	0.89 (0.06)	(-0.02:0.10)	-0.64	0.174
Underwater propulsion distance (UD, m)	2.29 (0.33)	2.61 (0.35)	(0.01:0.64)	-0.93	0.046
Head-wall distance when speed goes to 1.9 m/s (D19, m)	2.41 (0.36)	2.79 (0.38)	(0.02:0.72)	-0.85	0.037
Lateralization during push-off (LA,°)	-1.66 (5.81)	2.54 (3.24)	(-8.62:0.22)	-0.83	0.057
Horizontal impulse during the push-off (HPoL, N.s)	134.54 (43.06)	171.44 (48.96)	(-6.41:80.22)	0.80	0.090

Speeds (VOut, V1mR, VG, VIn, and Vmax) were horizontal speeds of the swimmers' head.

Discussion

Our results showed that the variables related to swimming speed and tumble turn technical skill (e.g. high speed during the approach, at the end of the push-off and after the turning wall, lateral impulse during placement, body alignment during the push-off, horizontal impulse and lateralization of the push-off, underwater propulsion distance) were higher in elite female swimmers.

These results confirm our general hypothesis that the turn performance is related to several technical skills variables. These results compare the recent study by David et al. (2022) who fitted a linear mixed effects model in 18 elite swimmers (10 females and 8 males) and reported significant negative effects of wall contact time (-4.22, $p < 0.001$), maximum force push (-2.18, $p = 0.04$), approach speed (-4.83, $p = 0.02$), wall adaptation time (-2.68, $p = 0.002$), and exit speed (-9.52, $p < 0.001$) on the 5mRTT.

Approach speeds

Swimmers in the elite group swam faster than sub-elite swimmers 3 m before the wall and during the approach which is consistent with recent work by Marinho et al. (2020) who demonstrated in elite swimmers faster approach speeds (5m-in, the time between reaching the 45 m mark and contact with the wall) in 100 m races compared to 200 m races. In our study, the duration of this phase was likely related to a higher swimming speed (the average performance of the elite swimmers in the 200 m front crawl was 01:59.5 sec. versus 02:15.30 sec. for the sub-elites). These outcomes align with the research of Born et al. (2021) who observed for the 5 m-in a difference of 24 hundredths between the 25th and 90th percentiles (3.28 sec. for 01:54.95 sec. vs. 3.52 sec. for 02:03.04 sec.) on elite competitors in the European Short Course Championships. Faster approach times for elite versus sub-elite swimmers have also been identified for other strokes such as breaststroke (Sánchez et al., 2021), backstroke, and butterfly (Born et al., 2021), likely due to higher energy and technical qualities allowing for higher swim speed. Another explanation is better regulation and less decrease in velocity on approach to the turn wall (David et al., 2022; Seifert et al., 2018; Simbana et al., 2018) obtained in particular by taking visual information (Seifert et al., 2018) and adjusting the turning distance (i.e. tuck index) (David et al., 2022).

Speeds after the turning wall

Elite swimmers moved faster than sub-elite swimmers at the end of the push-off and 3 m after the wall. This outcome is consistent with recent work reporting faster underwater speed (between the contact and head breaking through the water surface) and shorter 5-m out in the fastest races (Marinho et al., 2020) and among the best swimmers in the 200 freestyle (18 hundredths of a difference between the 25th and 90th percentiles, i.e. 2.09 sec. for 01:54.95 sec. vs. 2.27 sec. for 02:03.04 sec) (Born et al., 2021; Marinho et al., 2020).

Speeds at the end of the push-off

Just before the end of the push-off, elite swimmers reached their maximal speed that was significantly greater than the sub-elite swimmers. As already observed in other research, these better push-off in elite swimmers is probably related to a higher horizontal push-off impulse (Jones et al., 2018; Pereira et al., 2006) and to lateralization of the push-off

(Puel et al., 2012; 2022) which were two variables significantly correlated with fast turn times. More practice by elite swimmers probably helped them maintain a higher horizontal speed further (at the end of the push-off) than sub-elite swimmers. This level of performance was likely related to exerting a lateral impulse allowing a more rectilinear trajectory, and/or adopting a more streamlined position along the push-off. These results are complementary to a recent work (Puel et al., 2022) that emphasizes that longitudinal (twisting) rotations during placement, and the depth of the glide phase after push-off were higher in the female swimmers who performed the best turn times.

Underwater swimming distances

Another important difference between the two groups was the propulsion distance underwater. The elite swimmers started the propulsion underwater 0.33 m further from the wall than the sub-elites which did not seem to relate to the difference in (standing) height between the two groups which was only 0.09 m. At this time, the horizontal speed was nearly the same for both group (1.88 m/s for elites and 1.87 m/s for sub-elites) and very close to the lower speed recommended by Lyttle et al. (2000, i.e. 1.90 m/s). This difference in distance could indicate that sub-elite swimmers were not as efficient as elite swimmers on contact and glide phases. The gliding phase has been very well documented by Goya et al. (2003) for a cohort of 30 subjects, male and female swimmers, from trained to elites. The swimmer must be aligned during the push-off, a posture that was more accentuated in expert swimmers.

Other authors have also studied the gliding phase using computational fluid dynamics (Marinho et al., 2013). In this study, the drag coefficient showed the lowest value in the prone position, followed by the lateral position with 45° rotations (0.29%, 0.15%, 0.01% increase in drag for 1.5, 2.0 and 2. 5 m/s, respectively), the lateral position with 90° rotations (1.03%, 0.94%, 0.64% increase), and the supine position (2.21%, 1.42%, 0.96% increase in comparison with the prone position), in which the highest value of drag coefficient was observed. In light of these results, it would seem that an efficient turn strategy would be to adopt a slightly lateral position when placing the feet, to twist by pushing on the wall (Puel et al., 2022) to achieve the glide in prone position.

Body extension during the push-off

All contact-calculated body extension indices were higher in trend for elite swimmers than for sub-elite swimmers (Figure 3). For the lower limbs, anterior studies indicate that contacting the wall with the legs more extended (about 100-120°) could shorten the turn time (Takahashi et al., 1983; Blanksby et al., 1996; Cossor et al., 1999; Araujo et al., 2010). On the upper body, no previous studies have analyzed the profile of swimmers during the contact. Moreover, the correlations calculated on the whole group showed a greater extension of the legs at contact, and at the start of the push in the fastest swimmers. The values of the two variables Contact Lower Limb extension index and Contact Upper Body extension index could demonstrate superior ability for elites who were better able to place their arms during the rotation by directing them forward in the main direction of next movement. These results indicate that the expert swimmers exhibited a better profile than the non-expert swimmers throughout the contact. In contrast, the non-experts' hands, forearms and arms were more flexed compared to the experts. At push-off, elite swimmers were more streamlined than sub-elite swimmers, thus maximizing the speed production due to the extension of legs. As lateral and vertical components of the contact force presented very few differences between groups, the horizontal component seemed to differ slightly on some parameters linked to an earlier and higher force peak for elite female swimmers.

Horizontal impulses during the push-off

This larger horizontal impulse during push-off in elite swimmers is consistent with the results of Miyashita et al. (1992) who had noted increasing powers of legs extension between age group (13 years), college (19 years) and American national level swimmers (18 years). However, in the present study, the horizontal impulse during push-off although superior among expert swimmers was not correlated with 3mRTT for the entire group. This result implies that a strong impulse is not enough to achieve a fast tumble-turn if it is not combined with technical capabilities such as body extension to reduce resistance and push-off lateralization (produce a push-off with an angle that allows to transform a lateral torsional movement into a straight trajectory). The effects of the temporal position of the force peak on the speed curve were introduced by Klauck (2005). Using an underwater push-off simulation, the author emphasized the influence of water and its drag effect on the swimmer speed. Unlike an aerial push-off (e.g., countermovement jump), the temporal distribution of the force applied on the turning wall determines the end-of-contact speed. Klauck (2005) argued that better turns could be performed with a force peak occurring closer to the end of the contact that permits the highest possible end-of-contact speed. However, the elite female swimmers did not perform turns in this sequence (Figure 4) as their force seems to peak before the sub-elites', and could thus contribute to the highest horizontal push-off impulse.

Lateral impulse during placement and lateralization of the push-off

For the full group of swimmers, the signs of the correlation coefficients (direction of effect) for the variables of lateral impulse during placement, and lateralization, of the push-off indicate that the best turns were characterized by a higher lateral impulse during placement as well as a greater lateralization of the push-off. The high values of lateral impulse during placement could be the consequence of a fast turn and a high approach speed. The fastest swimmers also appeared to be better able to exert lateral force during the push-off, allowing them to move horizontally forward during the glide as proposed by Pereira et al. (2006).

Finally, one could argue that the difference in performance between the two groups was related to the age difference. However, all of the swimmers of both groups were female adults according to the criteria as described by Marshall and Tanner (1969). Further evidence of physical maturity in the youngest participants was that their growth (in stature) was limited over the two years following the experiment (data not shown) in agreement with the conclusions of Silva et al. (2007). In addition, it should be noted that approximately ten years after the data was collected, no swimmer from the sub-elite group reached the elite level. We interpret this outcome that the differences observed were most likely largely related to the level of expertise, and superior training in the elite group and not the age differences per se. Thus, the criteria that differentiate the turn and swimming performances of the two groups of swimmers were their expertise, body height and body mass. These differences corresponded to more years of practice and training for elite swimmers, indicated by higher force and muscle mass and better performance at the 200 m front crawl (L) and at the tumble turn (3m RTT). However, these differences -which should give proportionally greater attribution to factors related to the strength of the swimmers- were not revealed by our results, thus supporting the assertion that mastery of the technical features of the tumble turn could be essential to make the best turns (Puel et al., 2012, 2022). The age and the level of practice of the expert swimmers probably also explain the results obtained. Indeed, the additional years of practice, expert coaching, and in some circumstances, biomechanical support, likely all contributed to improved performance. Coaches and practitioners should structure drills to train swimmers to approach the wall at the highest possible speed, direct the push-off horizontally forward, and then streamline to create the highest speed.

Limitations of the study

Once the values were normalized by individual 100-m performance, only the variable Vout - the horizontal speed of the swimmers' 3 m after the wall - remained significantly different between the elite and sub-elite groups. It appears that the differences in kinematic variables (approach and full turn times) are primarily related to differences in swimming speed between the two groups of swimmers. Conversely, the horizontal velocities of the swimmers 3 m after the wall (V out) seem to be more dependent on the specific technical skills of the tumble turn (pushing on the wall, profiling, swimming underwater). A methodological limitation must be mentioned. As a fixed point was used to determine the end of the turn phase (3mRTT), taller swimmers reach this point earlier, but with less distance covered. The measurements were made between 2008 and 2010. From 2010 to the present time the tumble turn technique has evolved. Some swimmers prefer to push off on their back, although others prefer to incorporate a quarter twist so that they push off on their side. This study was conducted on world-class swimmers in an exploratory observational design. Therefore, our results must be interpreted with caution and need to be confirmed by experimental studies conducted on a larger cohort of elite swimmers. Further research to investigate the effects of fatigue on the technical skill responses of the tumble turn should be conducted. A specific study devoted to the spinning movement to determine the best time to perform this skill during the tumble turn would also be useful.

Conclusion

Elite swimmers showed a greater turning skills than their sub-elite counterparts in the kinematic speed and streamlined postural placement variables, while for the kinetic variables only the horizontal impulse during the push-off was higher.

Elite female swimmers of various levels had higher approach and push-off speeds, were more streamlined through the contact, and a higher lateralization of the push-off, than their sub-elite counterparts. Moreover, the difference between groups in distance at the end of the glide (at a similar horizontal velocity) showed that sub-elite swimmers were not as effective on contact and glide phases. The design, implementation and use of new motion analysis tools in swimming offers new insights and opportunities to improve technical skill and performance.

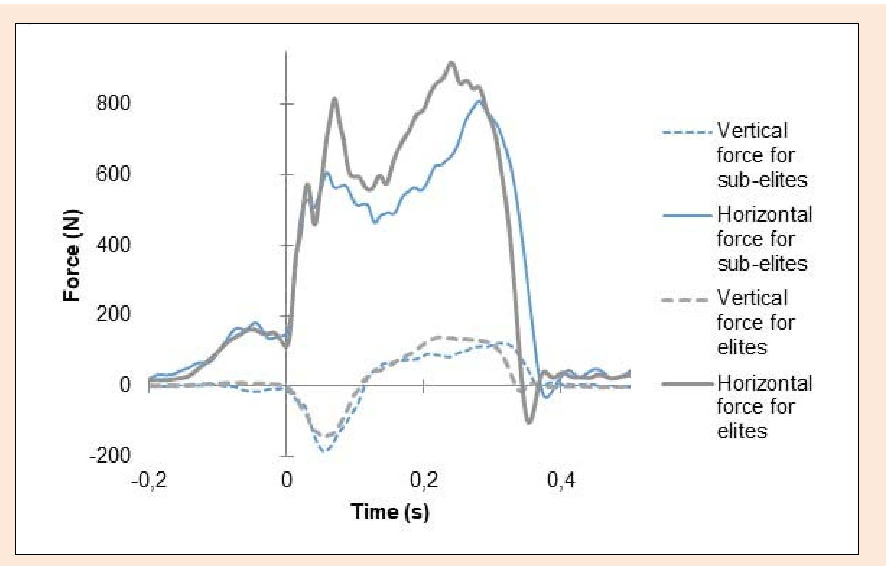

Figure 4. Vertical (dashed line) and horizontal (continuous line) components of the force applied on the turning wall by sub-elite (blue/thin) and elite (gray/thick) female swimmers. Lateral means were not shown here because swimmers of a same group could perform either a left- or a right-twisted turn. Averaging this component does not make sense.

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Key points

- Swim speeds were faster for expert swimmers 3 m before the turning wall, 1 m before the rotation, at the end of the push-off on the force platform and 3 m after the wall.
- For the technical skill variables, in the 18 swimmers the 3mRTT was significantly correlated with greater postural extension at key moments of the start of contact, start of push-off, end of push-off.
- For kinetic variables the elite swimmers were characterized by higher push-off impulse and lateralization of push-off. For the group as a whole, performance was significantly correlated with the lateral impulse during placement, the maximum horizontal force and the lateralization of the push-off.

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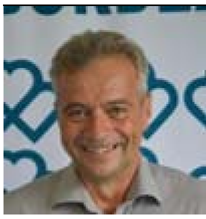

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