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Explosive lower limb extension mechanics: An on-land vs. in-water exploratory comparison

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ABSTRACT

During a horizontal underwater push-off, performance is strongly limited by the presence of water, inducing resistances due to its dense and viscous nature. At the same time, aquatic environments offer a support to the swimmer with the hydrostatic buoyancy counteracting the effects of gravity. Squat jump is a vertical terrestrial push-off with a maximal lower limb extension limited by the gravity force, which attracts the body to the ground. Following this observation, we characterized the effects of environment (water vs. air) on the mechanical characteristics of the leg push-off. Underwater horizontal wall push-off and vertical on-land squat jumps of two local swimmers were evaluated with force plates, synchronized with a lateral camera. To better understand the resistances of the aquatic movement, a quasi-steady Computational Fluid Dynamics (CFD) analysis was performed. The force-, velocity- and power-time curves presented similarities in both environments corresponding to a proximo-distal joints organization. In water, swimmers developed a three-step explosive rise of force, which the first one mainly related to the initiation of body movement. Drag increase, which was observed from the beginning to the end of the push-off, related to the continuous increase of body velocity with high values of drag coefficient (C_D) and frontal areas before take-off. Specifically, with velocity, frontal area was the main drag component to explain inter-individual differences, suggesting that the streamlined position of the lower limbs is decisive to perform an efficient push-off. This study motivates future CFD simulations under more ecological, unsteady conditions.

1. Introduction

Water has a greater density and viscosity than air (water is fifty-five times more viscous than air at 20 °C, Denny (1993)), which impacts body equilibrium and displacement. Indeed, swimmers must (i) propel themselves in a horizontal position (typically, this is performed vertically on land), (ii) with the help of their four limbs (lower limbs on land) and (iii) in a moving environment offering both support and resistances (support is stable and rigid on land, and aerodynamics resistances are restricted). Consequently, swimming performance depends on the interaction of propulsive and resistive forces (Toussaint, 2002). Swimming differs from other popular sports since athletes' body translates horizontally to minimize water drag.

Race performance is positively correlated with the total time spent during the turns, depending on the race distance ($r = 0.80$–0.90; Arellano et al., 1994). According to Mason and Cossor (2001), the most relevant aspect of the turn performance is the *pushing-off the wall* action (i.e., a powerful extension of the lower limbs). Efficiency in this phase is determined by three essential components: an effective peak push-off force, an appropriate time spent in contact with the wall and a good streamlined position to limit the amount of drag during the push and the glide phase (Lyttle et al., 1998, 1999; Mason and Cossor, 2001). Classically, water drag was estimated from inverse dynamics approach,

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including wall push reaction forces and body Center of Mass (CM) acceleration, obtained by video recordings (Klauck, 2005; Lyttle et al., 1999). Such studies reported resultant drag (D) and effects of body velocity (v) without any information about drag coefficient (C_D) and frontal area (S), the two main parts of the drag largely affected by body position (Clarys, 1979). In consequence, the effects of drag parameters on the push-off performance were not explicitly characterized. Vilas-Boas et al. (2010) compared D, C_D and S values through inverse dynamics and planimetry in the two gliding positions of the breaststroke turn. Nevertheless, S was analyzed independently from the remaining two parameters.

Computational Fluid Dynamics (CFD) is a potent numerical tool to compute D, C_D and the instantaneous projected S (Bixler and Schloder, 1996). For instance, this analytical tool reinforced results of experimental approaches that investigated the impacts of accelerated movements through water to increase propulsive drag (i.e., estimation of drag and lift forces developed by a swimmer's hand in Bixler and Schloder, 1996). Moreover, CFD technique has the advantage of showing detailed characteristics of fluid flow around the swimmer's body (Marinho et al., 2011). Precisely, it may help evaluate the perturbations and turbulences in the behavior of water molecules (leading to *unsteady* flows; Gomes and Loss, 2015) following a swimmer's displacement in the aquatic environment. Because of the complexity of these ecological situations, simplifications are often made in numerical approaches to solve fluid flow equations, assuming a steady aquatic environment around the moving swimmer. In this way, previous CFD studies segmented a whole movement into *different successive positions*, to approach the fluid behavior in dynamical conditions. Using this strategy, Zaïdi et al. (2008) and Popa et al. (2014) characterized drag as a function of head position during gliding.

Powerful lower limb extensions are classically studied on land, where athletes perform this movement vertically, against their own body weight or with additional loads acting as resistances (Cormie et al., 2008). CM velocity, force development or thrust power are common variables measured to explain athletes' strategies when performing a vertical jump. Such movement is very close to the horizontal underwater wall push-off. More precisely, in water, the performance is strongly dependent on the body position (influencing both projected frontal area and drag coefficient) and fluid properties (e.g., depth in which the movement is performed and whether the fluid is in motion or not). On land, the body conformation and the distribution of masses act as performance-related parameters. Therefore, the main movement limitations that arise underwater are linked to *drag* (i.e., water is challenging the movement), while *gravity* mainly constrains the extension performed on land. By comparing the mechanical properties of both push-off, we sought to investigate the different *adaptive behaviors* a swimmer may develop to reach the task goal in the constraining aquatic environment. Consequently, kinetics and kinematics comparisons between a maximal lower limb extension performed in both conditions would provide additional insights into the impacts of aquatic constraints on lower limbs push-off strategy and hence, on performance. An underlying objective was to properly characterize the constraints of the underwater movement to develop swimmers' abilities in order to become efficient in the push-off sequence of a competitive turn. We hypothesized that resistive aquatic environment would prompt swimmers to reach lower take-off velocities (i.e., lower performance) in comparison to on-land condition. Additionally, to deeply examine the effects of aquatic constraints on the push-off mechanics, the different components of drag (v, C_D and S) will be investigated using a quasi-steady CFD approach.

2. Methods

2.1. Participants

Two male swimmers, volunteered to participate in this study [mean ± SD for age: 22 yr, height: 1.82 ± 0.03 m, and weight: 77.0 ± 2.8 kg]. They were previously informed about the experiment and signed a consent form approved by the local ethics committee. The limited number of participants involved in this study is due to the complexity of the CFD approach.

2.2. Experimental protocol

Swimmers performed two trials of maximal push-off against the wall, 0.8-m underneath the water surface to avoid significant wave drag (Vennell et al., 2006) and to reproduce ecological race conditions: arms extended over the head (shoulder flexed), hands joined and palms down. Then, swimmers performed two maximal on-land squat jumps with identical body configuration than during underwater push-off (Fig. 1). The replication of the body conformation consisted of measuring all joint angles of the lower limbs during the underwater push-off (Fig. 1), before reproducing it on land. Since no mobility measurements were performed, we asked swimmers to hold their arms firmly extended overhead (i.e., horizontally underwater and vertically on land). Analyses were conducted on each push-off yielding to the highest CM velocity.

2.3. Data collection

Five anatomical landmarks (humerus' greater tubercle, great trochanter, lateral condyle of the knee, lateral malleolus and head of the fifth metatarsal) were filmed during the underwater push-off by a digital video camera (Sony® HDR-CX160E 50 Hz, Tokyo, Japan), positioned 5-m sagittally, 0.8-m deep, in a waterproof housing (SONY Sports pack SPK-CXA, Tokyo, Japan). The video footage was calibrated using a 2-m rigid calibration perch with nine control points (20-cm spacing).

Reaction forces at swimmers' feet were recorded by two underwater extensometric force plates with a surface of 0.5 × 0.5-m, sensitivity of 2 N, error <1% and natural frequency of 60 Hz, mounted on a specially-built support fixed to the pool wall with a sampling frequency of 2000 Hz (de Jesus et al., 2013). Squat jump forces were registered by two force plates (Bertec Corporation, Columbus, OH, USA) with a surface of 0.6 × 0.9-m and sampling frequency of 400 Hz. Force plates were connected to an analogue-to-digital converter (National Instruments, NIcDAQ-9172). Underwater video footage and force signals were synchronized with a starter device (ProStart, Colorado Time Systems Corporation, Colorado, USA), which simultaneously produced a light signal to the video system and a trigger signal to the converter.

Three-dimensional virtual, realistic body models (with goggles and cap, Fig. 2) were created with Mephisto 3D full body scanner and software (Mephisto 3D, 4DDynamics, Antwerp, Belgium). The scan system had a texture resolution of 12.4 megapixels, and a point accuracy of 0.15 mm in average, creating 3D models composed of more than 70,000 cells. Swimmers' bodies were scanned in three different positions (beginning of the push-off, middle part, and position before take-off) to obtain a general overview of the drag history over the whole push: upper limbs extended above the head and lower limbs adopting a configuration similar to the one observed in water.

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