The determinant factors of undulatory underwater swimming performance: a systematic review

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Abstract

The prominence of undulatory underwater swimming (UUS) has been clearly observed during recent international events. Improvement of this phase is important for overall performance. The aim of this systematic review was to identify the key factors that modulate UUS performance and provide coaches and sports science practitioners with valuable and practical information to optimize it. PubMed, Web of Science, Scopus, and SPORTDiscus databases were searched up to 14 October 2021. Studies involving competitive swimmers and which included UUS performance assessment were considered. Methodological quality assessment was conducted for the included articles. From the 193 articles screened, 15 articles were included. There was a substantial body of research conducted on kicking frequency, vertical toe and body wave velocity, angular velocity of the joints, distance per kick, joint amplitudes and mobility, and body position in UUS performance. However, further investigation is required for muscle activation and muscle strength influence. The results from this review contribute to understanding of how to optimize UUS performance, identifying the key aspects that must be addressed during training. Specifically, the caudal momentum transfer should be maximized, the upbeat duration reduced, and the frequency that best suits swimmers’ characteristics should be identified individually.

Keywords: dolphin kick, swimmers, biomechanics, propulsion, sprint.

Introduction

Aside from the dive start, the highest swimming velocities are achieved during the underwater phase of butterfly, backstroke, and front crawl events and this phase of events id recognized as being one of the most influential variables on swimming performance (Mason & Cossor, 2000). Throughout the underwater phase, swimmers propel themselves forward by performing the undulatory underwater swimming (UUS) after a short glide. The prominence of UUS has been clearly observed during recent international events, where most of the swimmers seize the opportunity to maximize their performance in the underwater phase (limited to 15 m after each wall (FINA, 2013)) as an important contribution to their overall performance (Veiga, Cala, Mallo, & Navarro, 2013). This fact has led to a large increase in the volume of research conducted, since the review by Connaboy, Coleman, & Sanders (2009), with the aim of understanding the key parameters in UUS performance (Atkinson & Nolte, 2010; Connaboy et al., 2016; Higgs, Pease, & Sanders, 2017; Ruiz-Navarro et al., 2021). For this reason, it is necessary to provide coaches and swimming specialists with an up-to-date review of UUS to optimize UUS training and therefore to improve overall swimming performance.

The UUS is a leg-dominated technique (Higgs et al., 2017) which achieves propulsion by performing body undulations while in a streamlined position with the arms extended and held together over the head (Arellano, Pardillo, & Gavilán, 2002; Connaboy, Coleman, Moir, & Sanders, 2010). The propulsion is produced by a “body wave”, which increases in amplitude as it travels caudally throughout the body in a “whip-like” action (Gavilan, Arellano, & Sanders, 2006; Sanders, Cappaert, & Devlin, 1995; Ungerechts, 1983). When swimmers are at least 0.5 m below the water surface, the wave drag is considerably reduced (Tor, Pease, & Ball, 2015), while the fusiform streamlined shape decreases pressure drag (Connaboy et al., 2009).

The UUS is a cyclic motion, which has been divided into three phases, the upbeat phase, a second upbeat phase, and the downbeat (Arellano et al., 2002; Shimojo, Sengoku, Miyoshi, Tsubakimoto, & Takagi, 2014). The second upbeat phase is initiated when the feet trajectory change from a vertical to a more horizontal displacement, due to the start of the knee flexion (Arellano et al., 2002). Nevertheless, to facilitate its grasp, most of the researchers have used 2 phases (Connaboy et al., 2010, 2016; Higgs, Pease, & Sanders, 2015; Ruiz-Navarro et al., 2021; Shimojo et al., 2019a): the upbeat and downbeat (also referred in the literature as up-kick and down-kick). In a prone position the upbeat is characterized by the combination of hip extension and knee flexion while the downbeat is executed by the combination of hip flexion and knee extension. These phases are delimited by the turning points of the toe landmark (Higgs et al., 2017). However, due to human body anatomy (Stefan Hochstein & Blickhan, 2014; Ungerechts, 1985) there are differences between these two phases and their contribution to total propulsion (Atkison, Dickey, Dragunas, & Nolte, 2014).

Considering the complexity of the UUS movement, the aims of this systematic review were to identify the biomechanical, physiological and/or neuromuscular factors that have been identified in the literature as influencing UUS performance and to provide coaches and sports science practitioners with valuable and practical information that may be of interest when implementing this movement during training.

Materials and methods

Definitions of terms related to swimming biomechanics are presented in Table 1. This systematic review was completed in accordance with the guidelines provided in the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) statement (Page et al., 2021). The review protocol was not registered.

[Please insert Table 1 near here]

Search strategy

A systematic literature search was performed encompassing publications from inception to 30 September 2020 on four international electronic databases: PubMed, Web of Science, Scopus, and SPORTDiscus. The complete search strategy used in PubMed was as follow: ((((Undulatory underwater swimming) OR (Underwater undulatory swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic)). To adjust to the nuances or requirements of the other databases searched, the specific search terms were modified as shown in Supplementary Table 1. An update of the database search up to 14 October 2021 was conducted following the same steps as the ones performed during the original search, with the exception that in this case, publications were encompassed from 30 September 2020 to 14 October 2021 (Supplementary Table 2).

Eligibility criteria

Inclusion criteria were defined as follows: 1) studies involving competitive swimmers with at least three years of competitive experience; 2) studies that measured the influence of biomechanical and physiological variables on UUS performance; 3) studies with outcome measures related to UUS performance.

Exclusion criteria were defined as follows: 1) studies that included participants who were non-swimmers (i.e., water polo players, triathletes, scuba divers) or animals; 2) studies in which underwater undulatory swimming performance was not measured (i.e., time to cover a distance or velocity); 3) reviews, case-studies, poster, conference abstracts, or presentations; 4) studies not written in English.

Study selection

Two independent researchers performed the selection process of relevant articles First, all the studies obtained from the search of the databases were inspected, duplicate articles were removed, and titles and abstracts were independently screened. The researchers applied the eligibility criteria defined above and disagreements were discussed until consensus was reached. Then, the same procedure was conducted after full-text screening of the remaining articles for the final inclusion or exclusion decision. Finally, the reference lists of the included articles were checked for relevant articles that might not have been identified in the initial databases search.

Data extraction

The extraction process was conducted by one researcher and double-checked by another independent researcher. The items extracted were: 1) study reference; 2) main purpose; 3) number of participants per sex, age, and competitive level; 4) test performed; 5) UUS velocity and kick frequency; 6) variables measured; and 7) main findings. When there were differences between data extracted initially and the double-checking, the issue was discussed between the two researchers until consensus was reached.

Quality assessment

Due to the absence of a validated quality assessment tool appropriate for sports performance, some authors (Gupta, Morgan, & Gilchrist, 2017; Thng, Pearson, & Keogh, 2019) have employed the Newcastle–Ottawa Quality Assessment Scale (NOS) (Wells et al., 2014) for cohort studies in reviews of athletes; however, the use of the adaptation for cross-sectional studies is not yet recommended, since a formal version is required (Moskalewicz & Oremus, 2020). Hence, Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews (Moola et al., 2017), specifically designed tool to assess quality in cross-sectional studies was used. This tool has been used lately (Molina-Garcia et al., 2019) consisting of eight items with three possible answers (“*yes*”, “*no*”, and “*not applicable*”*).* A total score for each study provided a general indication of quality. The total score was obtained as the number of positively scored criteria divided by the total number of criteria. When the quality score was 0.75 or higher, the study was considered ‘high quality’ and when the quality score was lower than 0.75, the study was considered as ‘low quality’ (Molina-Garcia et al., 2019). Two independent reviewers conducted this process. and disagreements, about the scores of the studies, were discussed until both researchers agreed.

Results

Article identification

In the first main search, 168 articles were identified and 66 duplicates were removed. After the screening of titles and abstracts of the remaining 109 articles, the full texts of a total of 32 articles were screened. Finally, 12 studies met the inclusion criteria and were subsequently included in this review. Some studies that met the inclusion criteria were excluded after the full-text read. For instance, the work by Hochstein & Blickhan (2014) was potentially considered; however, two of the participants were triathletes and therefore the study had to be excluded from this systematic review or the work by Matsuura, Matsunaga, Iizuka, Akuzawa, & Kaneoka (2020) which provided valuable information about muscle synergies during UUS, however, despite performance was measured, the significance of each synergy on performance was not reported.

The updated searches in October 2021 resulted in a total of 25 new articles, of which three new studies were eligible. The study selection process is described in Fig. 1. In total, therefore, we screened 193 records which resulted in 15 studies being included in this systematic review.

[Please insert Fig. 1 near here]

Description of the included articles

There were no eligible papers prior to 1999, ranging the years of publication of the 15 papers from 1999 to 2021. Nine of them were subsequent to the previous review published in 2009 (Connaboy et al., 2009). The populations studied were national swimmers (n=6), international swimmers (n=3), and competitive swimmers (n=6). Two of the aforementioned studies had a heterogeneous sample of swimmers with variation in performance level. Five of the studies had both male and female participants, six had all male participants, and only one had all female participants. The participants' sex in the remaining three studies was not reported. Sample size ranged from 6 to 47 participants, with 12 of the articles $\geq$ 10. The sample mean age ranged from 16 to 22 years, with nine of the studies having swimmers over 18 years and only six of them having swimmers under 18 years. The characteristics of the papers are presented in Table 2.

[Please insert Table 2 near here]

Quality assessment

The initial agreement between both researchers had a substantial inter-rater reliability (κ= 0.64). Among the included articles, 10 of them were categorized as "high quality" and 5 as "low quality". The percentage of studies meeting each quality criteria is shown in Supplementary Table 3.

Undulatory underwater swimming measures

Kinematic variables

The kick frequency has been the most extensively researched in the articles included, being assessed in 13 of the 15 papers included (Alves, Lopes, Veloso, & Martins-Silva, 2007; Arellano, Gavilán, & Garcia, 1999; Atkison et al., 2014; Connaboy et al., 2016; Crespo, Ruiz-Navarro, Cuenca-Fernández, & Arellano, 2021; Houel, Elipot, André, & Hellard, 2013; Ikeda et al., 2021; Shimojo et al., 2019b; Shimojo et al., 2014; Wądrzyk, Staszkiewicz, Kryst, & Żegleń, 2019; Wadrzyk, Staszkiewicz, Zeglen, & Kryst, 2021; Willems, Cornelis, De Deurwaerder, Roelandt, & De Mits, 2014; Yamakawa, Shimojo, Takagi, Tsubakimoto, & Sengoku, 2017a). When the kick frequency increased above the preferred frequency, UUS velocity did not change (Shimojo et al., 2014; Yamakawa et al., 2017a) but the reduction in kick frequency led to the decrease of UUS velocity (Shimojo et al., 2014; Yamakawa et al., 2017a), lower peak and mean vertical toe velocity during the upbeat and body wave velocity (Yamakawa et al., 2017a). The UUS velocity was positively correlated with peak vertical toe velocity and body wave velocity, during both the upbeat and the downbeat (Higgs et al., 2017).

Elite swimmers had higher hip, knee, and ankle peak angular velocity than non-elite swimmers (Wang & Liu, 2006), being the UUS velocity related to peak knee and ankle angular velocity (Connaboy et al., 2016), mean knee and peak hip angular velocity (only during the upbeat) (Higgs et al., 2017). The distance per kick correlated with UUS velocity (Wądrzyk et al., 2019), only during the downbeat (Atkison et al., 2014) and it was inversely related to changes in kick frequency (Shimojo et al., 2014). The toe amplitude was not correlated with UUS velocity during UUS trials (Atkison et al., 2014; Connaboy et al., 2016; Higgs et al., 2017; Wądrzyk et al., 2019) and it was reduced when the kick frequency was increased above the preferred kick frequency (Yamakawa et al., 2017a). The non-dimensional kick amplitude (i.e. amplitude normalized to body height) was increased when the kick frequency was reduced below the preferred kick frequency (Shimojo et al., 2014). When measured during the underwater phase of a grab start, the trunk, thigh, leg, and foot angle of attack correlated negatively with UUS velocity (Houel et al., 2013).

Kick phases

Nine of the studies reported the results of UUS measured as a single phase (Connaboy et al., 2016; Houel et al., 2013; Shimojo et al., 2019b; Shimojo et al., 2014; Wądrzyk et al., 2019; Wang & Liu, 2006; Willems et al., 2014), six studies differentiated two phases (i.e. downbeat and upbeat) and reported the results for each phase. (Alves et al., 2007; Arellano et al., 1999; Atkison et al., 2014; Higgs et al., 2017; Ikeda et al., 2021; Yamakawa et al., 2017a). Note that, Ikeda et al.(2021), defined the two phases as acceleration and deceleration phase, but in this manuscript, these phases will be referred to as downbeat and upbeat, respectively. The sagittal kick symmetry among downbeat and upbeat was positively correlated to a higher UUS velocity (Atkison et al., 2014). The downbeat duration was shorter than the upbeat duration (Arellano et al., 1999; Atkison et al., 2014; Higgs et al., 2017; Yamakawa et al., 2017a). The UUS and mean vertical toe velocities were greater during the downbeat compared to the upbeat (Atkison et al., 2014; Yamakawa et al., 2017a). There was a very large positive correlation between the velocity during the upbeat and UUS velocity (Atkison et al., 2014).

Joint mobility

In-water and on land joint range of motion have been found to be related to UUS performance (Connaboy et al., 2016; Ikeda et al., 2021; Shimojo et al., 2019b; Wądrzyk et al., 2019; Willems et al., 2014). The lower trunk range of motion was positively correlated with the UUS velocity during both the upbeat and downbeat (Ikeda et al., 2021). The knee range of motion was negatively correlated with UUS velocity (10.3%velocity variation), only when ‘participants’ was set as the fixed factor (Connaboy et al., 2016).

Only female knee range of motion was negatively correlated with UUS velocity (Wądrzyk et al., 2019). The ankle range of motion was not correlated with UUS velocity (Shimojo et al., 2019b; Willems et al., 2014). When the ankle joint mobility was restricted, the UUS velocity decreased significantly (Shimojo et al., 2019b; Willems et al., 2014).

Body position

In two out of the fifteen included papers, dorsal underwater kicking was assessed (Alves et al., 2007; Arellano et al., 1999) and lateral underwater kicking was assessed in one (Alves et al., 2007). The UUS velocity, phase duration, kick frequency, distance per kick, joint amplitudes, or Strouhal number were found to be similar in dorsal and prone kicking (Alves et al., 2007; Arellano et al., 1999). There were significant differences in the angle of attack of the trunk and body oscillation in dorsal kicking than in prone kicking (Arellano et al., 1999). In lateral kicking there was higher ankle, knee, hip, shoulder, elbow, wrist, and hand amplitude of motion than in either prone or dorsal kicking (Arellano et al., 1999).

Muscle strength and anthropometrics

Muscle strength was assessed in only one study (Willems et al., 2014). The dorsal flexors and internal rotators isometric strength were significantly related to UUS velocity. In young swimmers, no significant correlation was obtained between somatic build and UUS velocity (Wadrzyk et al., 2021)

Muscle activation

The UUS velocity was positively correlated with the co-active phase of the rectus femoris - biceps femoris muscles and the co-active phase of the tibialis anterior - gastrocnemius muscles. The muscles' activation changed when the kick frequency varied from the preferred kick frequency (Yamakawa et al., 2017a). A high-intensity warm-up protocol elicited a post-activation performance enhancement in UUS (Crespo et al., 2021).

Discussion

The purpose of this systematic review were to identify the biomechanical, physiological and/or neuromuscular factors that have been identified in the literature as influencing UUS performance and to provide coaches and sports science practitioners with valuable and practical information identify the key factors of UUS performance and provide coaches and sports scientists with valuable and practical information to optimize it. There was a substantial body of research conducted to address the importance of kicking frequency, vertical toe and body wave velocity, angular velocity of the joints, distance per kick, joint amplitudes and mobility, and body position in UUS performance. However, other factors such as the muscle co-activation, the influence of strength, or the anthropometric influence require further investigation.

Kinematic variables

Kick frequency is known as one of the most important factors in UUS performance. Nevertheless, while some studies have reported positive correlations with UUS velocity (Alves et al., 2007; Houel et al., 2013) others did not find significant association. The difference between these studies relied on the homogeneity of the sample. In homegeneous sample of national swimmers, there was a positive association(Arellano, Pardillo, & Gavilan, 2003; Arellano et al., 2002), meanwhile in a heterogeneous sample of swimmers (i.e., high inter-variation in FINA points) no correlation was found (Atkison et al., 2014; Ikeda et al., 2021; Wądrzyk et al., 2019). Hence, this might indicate that kick frequency plays an important role when having highly skilled swimmers, but other kinematic variables might be more important in swimmers with less advanced UUS skills.

It is worth noting that a lack of correlation (which relies on a linear relationship) doesn't necessarily mean that the kicking frequency isn't important, because it might have an optimum that is best represented as a parabolic relationship or it might be exponential in nature. In fact, increasing the kick frequency above the preferred frequency seems to be counterproductive as UUS velocity remains unchanged while the amplitude, horizontal distance per kick, and Froude efficiency were negatively affected (Shimojo et al., 2014; Yamakawa et al., 2017a). Although no multi-task effect was apparent when controlling the kick frequency with a metronome (Yamakawa, Shimojo, Takagi, Tsubakimoto, & Sengoku, 2017b), it was observed that the muscle co-activation increased when increasing the kicking frequency above the preferred frequency. Based on the lower muscle co-activation showed by more skilled swimmers in flutter kicking than in recreational swimmers (Matsuda et al., 2016), it was suggested that a training period might be required to reduce such muscular co-activation and obtain performance improvements (Yamakawa et al., 2017a).

The maximum vertical velocity of the toe was correlated with UUS velocity during the upbeat (Atkison et al., 2014; Higgs et al., 2017), but the results were incongruous during the downbeat (Atkison et al., 2014; Higgs et al., 2017). The reason for the different outcomes might be related to the participants level, since the participants presented in the study of Atkison et al., (2014) had a high variation in performance level. Because humans have musculo-skeletal constraints that limit the upbeat phase (Loebbecke, Mittal, Fish, & Mark, 2009; Loebbecke, Mittal, Fish, & Mark, 2009), it is possible that all swimmers were able to reach the same vertical velocity of the toe, but only the most skilled swimmers were able to reach higher vertical toe velocity during the upbeat (i.e. better upbeat execution), being therefore the faster. Nevertheless, in a homogeneous sample of national swimmers (assuming that they can perform UUS properly) those who reached higher toe velocity in both phases were able to achieve higher UUS velocity than those with lower toe velocity (Higgs et al., 2017).

Regardless of the correlation between vertical toe velocity and body wave velocity, there is a level of independency between them, which indicates that a higher body wave velocity does not necessarily yield higher vertical toe velocity (Higgs et al., 2017). Moreover, the UUS propulsion generated by the "whip-like" action produced during the body wave is related to the angular velocities of the hip, knee, and ankle joints (Connaboy et al., 2016; Higgs et al., 2017; Wang & Liu, 2006). Special attention should be allotted to the hip extension during training (Higgs et al., 2015), as it was stated that better swimmers extend the hip before flexing the knees (Arellano et al., 2002). It should be noted that, despite the trunk undulation being important for maximizing propulsive efficiency (Nakashima, 2009), its action is not considered when measuring the hip action, and therefore the hip angular velocity might be misinterpreted (Higgs et al., 2017). Moreover, a higher mean angular velocity of the knee is related to the resistance generated by the horizontal motion of the toe during the latter phase of the upbeat (Connaboy et al., 2016; Higgs et al., 2017), which leads to a drop in UUS velocity (Wądrzyk et al., 2019).

The body displacement in the direction of swimming is not independent of the kicking frequency as a higher frequency means less time and distance travelled during the kick cycle. Due to the human anatomical constraints swimmers spend a longer time executing the upbeat than the downbeat (Atkison et al., 2014; Higgs et al., 2017; Yamakawa et al., 2017a) without reaching higher velocities (Higgs et al., 2015). This might be the reason why the distance per kick was positively associated with UUS velocity only during the downbeat (Atkison et al., 2014). Therefore, the distance per kick should not be used without considering it in conjunction with the kick frequency. Swimmers can certainly vary their distance per kick by varying their kick frequency (Shimojo et al., 2014); thus, a training period is required to establish the optimal combination of kicking frequency and distance travelled per stroke that will optimize the velocity of the swimmer.

The kick frequency is directly related to limb segment amplitude (Connaboy et al., 2016). Despite other landmarks being assessed, the end effector (i.e. toe) amplitude is the variable usually measured and related to UUS performance (Atkison et al., 2014; Connaboy et al., 2016; Higgs et al., 2017; Houel et al., 2013; Wądrzyk et al., 2019). However, the end effector (i.e. toe) amplitude, was not associated with UUS velocity (Atkison et al., 2014; Connaboy et al., 2016; Higgs et al., 2017; Wądrzyk et al., 2019). Only when the underwater phase of a grab start was studied, the toe amplitude at 5.5 m from the wall was negatively correlated with performance (Houel et al., 2013). This might be because the increase in the amplitude would increase the cross-sectional area perpendicular to the direction of motion which increases resistive drag, decelerating the body after the high velocity reached at the dive and therefore swimmers should avoid kicking until the kick contributes to speed rather than reducing speed (Takeda, Ichikawa, Takagi, & Tsubakimoto, 2009).

The UUS efficiency does not just depend on any simple kinematic parameter but is the result of the swimmer's technique, which encompasses different aspects of the body motion (Loebbecke et al., 2009). The amplitude of anatomical landmarks can be used to identify the UUS technique (Connaboy et al., 2009), which seems to be influenced by joint mobility (e.g. ankle mobility restriction evoke a higher knee flexion during UUS execution) (Willems et al., 2014). Moreover, an individual's own organismic constraints (e.g. limb segment lengths) also influence the UUS technique used by swimmers (Connaboy et al., 2016) and tall swimmers would need to reduce their end effector amplitude to have a kick frequency that is similar to short swimmers (Connaboy et al., 2009).

Kick phases

Unlike cetaceans such as dolphins, the musculo-skeletal constraints that limit the upbeat phase in humans (Loebbecke et al., 2009a, 2009b) evokes a 10% longer upbeat phase compared to the downbeat phase (Arellano et al., 2002; Atkison et al., 2014; Yamakawa et al., 2017a). Hence, despite that swimmers generate propulsion during the downbeat and upbeat phases (Atkison et al., 2014; Higgs et al., 2017; Ruiz-Navarro et al., 2021; Taladriz, Domínguez, Morales, & Arellano, 2015), the longer duration of the upbeat has been suggested as a recovery phase (Higgs et al., 2015). Nevertheless, Arellano et al., (2002) stated that during the first phase of the upbeat (i.e. when the feet displace vertically) the swimmers reached another peak velocity value and it was during the second phase of the upbeat (i.e. when the foot displacement is more horizontal) that the swimmers' velocity decreased. It is therefore possible that only the second upbeat should be reduced. More studies are needed to clarify the difference between these 2 phases of the upbeat.

Faster swimmers are able to reduce the duration of the upbeat (Atkison et al., 2014) with a consequent increase in swimming velocity (Higgs et al., 2017). This, highlighted the importance of executing the upbeat in a time similar to the downbeat (Atkison et al., 2014). In fact, latter authors stated that, while the downbeat execution was generally suitably performed, most of the swimmers struggled to perform the upbeat successfully (i.e., achieve similar velocity to the attained during the downbeat). Thus, swimmers should try to avoid using the upbeat as a recovery phase and reduce the upbeat duration to improve UUS performance (Atkison et al., 2014; Higgs et al., 2017). Indeed, a recent study found that after eight weeks of training, young swimmers improved UUS performance, mainly as a consequence of the upbeat phase enhancement (Ruiz-Navarro et al., 2021).

Joint mobility

Recently, Ikeda et al. (2021) reported a correlation between the lower trunk range of motion and the UUS velocity. Specifically, they showed how the lower leg angular displacement was increased by increasing the lower trunk range of motion, but these increase came without increasing the knee range of motion, which was negatively correlated with UUS velocity (Connaboy et al., 2016; Wądrzyk et al., 2019). Hence, the amplitude of the kick needs to be as a consequence of high lower trunk rather than a high knee flexion. Moreover, a lack of ankle mobility evokes compensatory movements (Ungerechts, Daly, & Zhu, 1998) such as higher knee flexion (Willems et al., 2014) which affected UUS velocity negatively (Arellano et al., 2002). Hence, the analysis of a single element of the UUS technique should be conducted while considering other segments (Wądrzyk et al., 2019).

Although neither the ankle range of motion measured on land nor the ankle range of motion during UUS were correlated with UUS velocity (Higgs et al., 2017; Wądrzyk et al., 2019; Willems et al., 2014) an ankle mobility restriction provoked a significant reduction in UUS velocity (Shimojo et al., 2019b; Willems et al., 2014). This might be because the ankle mobility restriction reduced ankle plantar flexion and internal rotation (Willems et al., 2014) and its effect on heaving and pitching motions (Ungerechts, Persym, & Colman, 2000), which would have a direct negative effect on shedding of vortices to generate propulsion (Anderson, Streitlien, Barrett, & Triantafyllou, 1998).

Body position

No significant differences have been reported between prone and dorsal UUS velocity (Alves et al., 2007; Arellano et al., 1999), and lateral UUS velocity (Alves et al., 2007). The main difference between prone and dorsal body positions seemed to lie in lower upper body oscillation and knee flexion (during the downbeat) while kicking in a prone position than in a dorsal position (Arellano et al., 1999). On the other hand, the upbeat velocity, frequency, and transverse amplitude of the joints were significantly different in the lateral position compared to the prone position (Alves et al., 2007). Yet, these differences were attributed to the lack of lateral kicking familiarization (Arellano et al., 1999). Moreover, UUS velocity was not related between conditions (Arellano et al., 1999). The authors speculated that despite being a similar movement, there is some independency between body positions.

Muscle strength and anthropometrics

Despite the importance of lower limb strength on swimming start and free swimming performance (Amaro et al., 2019; Cuenca-fernández et al., 2015; Muniz-Pardos et al., 2019; Thng et al., 2019), only the influence of ankle strength on UUS velocity has been studied (Willems et al., 2014). The positive association between dorsal flexion and internal rotation of the ankle (Willems et al., 2014) might be explained by the leg motion during the downbeat, as the ankles moved downwards with internal rotations and plantar flexion (Shimojo et al., 2019b). Then, the tibialis anterior muscles are activated, producing ankle dorsi flexion at the end of the downbeat and accelerating the body by the released jet flow (Shimojo et al., 2017). Based on the influence of hip and knee angular velocities on UUS velocity (Connaboy et al., 2016; Higgs et al., 2017), Future studies should be designed to assess the impact of the strength, of the muscles involved in hip and knee flexion and extension, on UUS performance.

On the other hand, despite somatic build has been related to swimming results (Moura et al., 2014; Nevill, Negra, Myers, Sammoud, & Chaabene, 2020) no relationship has been established with UUS performance (Wadrzyk et al., 2021). This study was only conducted with young male swimmers, and more researches with different samples are needed to clarify this issue.

Muscle activation

During the UUS movement, internal oblique, multifidus, rectus abdominis, erector spinae, rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius are activated in three synergies: 1) transition from upbeat to downbeat; 2) downbeat, and; 3) upbeat (Matsuura et al., 2020; Yamakawa et al., 2017a). The muscular activation pattern between agonist and antagonist muscles in the trunk and the thigh during the

UUS did not show co-activation in female competitive swimmers (Kobayashil, Takagi, Tsubakimoto, & Sengoku, 2016). Yet, the muscular co-activation phase between agonist and antagonist muscles of rectus abdominis - erector spinae (i.e. trunk) and rectus femoris - biceps femoris (i.e. thigh) had small and moderate positive associations with UUS velocity, respectively (Yamakawa et al., 2017a) (i.e. the higher the muscle co-activation, the higher the UUS velocity). These results were not consistent with the authors' hypothesis, as a negative association was expected. Hence, as the muscular co-activation was negatively correlated with Froude efficiency, it was postulated that swimmers increased UUS velocity by sacrificing the efficient muscular activation pattern (i.e. reciprocal activation) (Yamakawa et al., 2017a).

Together with muscle force output, the tendinous elastic energy contributes to UUS velocity, as a stretch-shortening pattern during the execution of UUS has been observed in the vastus lateralis (Sano et al., 2019). From these outcomes, swimmers should attempt to reduce the transition time between downbeat-upbeat to minimize the dissipation of the tendinous elastic energy. However, the potential role of other muscles involved on UUS performance remains unknown.

Limitations and future perspective

Future research should be conducted to address some limitations of previous research by: 1) stating clearly whether the sample used were male or female; and 2) by considering the action of proximal segments when examining single elements (e.g. the effect of knee action on the ankle, given that ankle restriction evokes an increase in knee flexion)

From a design standpoint, and based on the quality assessment (Supplementary Table 1) future studies should: 1) clearly show the inclusion and exclusion criteria for the sample used; 2) describe the sample's performance level (e.g. FINA points); and 3) identify and describe how to deal with potential confounders.

Future research should be conducted in an attempt to elucidate: 1) whether there is a maximal kick frequency that should not be surpassed; 2) the effects that UUS specific training could have on velocity, distance per kick, and kick frequency; 3) clarify the difference contribution between the two upbeat phases; 4) whether there is an optimal level of joint mobility; 5) the importance of joint muscle strength on UUS performance; and 6) muscle activation during UUS.

Conclusion

This systematic review identifies the key factors of UUS performance and provides valuable information about UUS that could aid coaches and sports science practitioners to improve swimmers' performance. The

UUS movement should be performed as a whip-like motion, maximizing the caudal momentum transfer (i.e. body wave velocity) and vertical toe velocity. The upbeat duration should be reduced and not used as a mere recovery phase. To optimize the upbeat, the hips have to be extended before flexing the knees avoiding the horizontal displacement of the toes during the latter phase of the upbeat. Special attention should be given to the knee and hip angular velocity in this phase. It is possible to benefit from the tendinous elastic energy stored during the UUS movement by reducing the duration of the transition between phases. The influence of kick frequency should be addressed when the movement is performed adequately, and not as a primary element when initiating the UUS movement. Higher frequency does not imply higher UUS velocity. The kick frequency is specific for each swimmer and the one that best fits every individual needs to be found. The UUS velocity can be improved by increasing the distance per kick while maintaining the swimmer's preferred kick frequency. The independence in UUS velocity between body positions suggests that the UUS movement must be developed in the same body position as the one used during competition. The amplitude of the kick should be driven by the range of motion of the hip and not the knee. The ankle joint mobility restriction evokes compensatory movements that negatively affect UUS performance. To enhance UUS performance, ankle plantar flexor and internal rotators strength have to be increased. There is no evidence about the other joints involved in UUS (i.e. hips and knees). An acute enhancement of the UUS performance can be elicited through a high-intensity warm-up protocol. Finally, apart from the key factors described above, certain individual characteristics need to be taken into account to avoid imposing the same UUS technique on all swimmers.

Disclosure statement:

The authors have no conflicts of interest to report.

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Figure legends and tables

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flowchart of the study selection process.

Table 1. Definition of the biomechanical swimming terms used in this review.

Table 2. Summary of the main purpose, participants background, methodology conducted, and main findings reported of the studies included in this review.

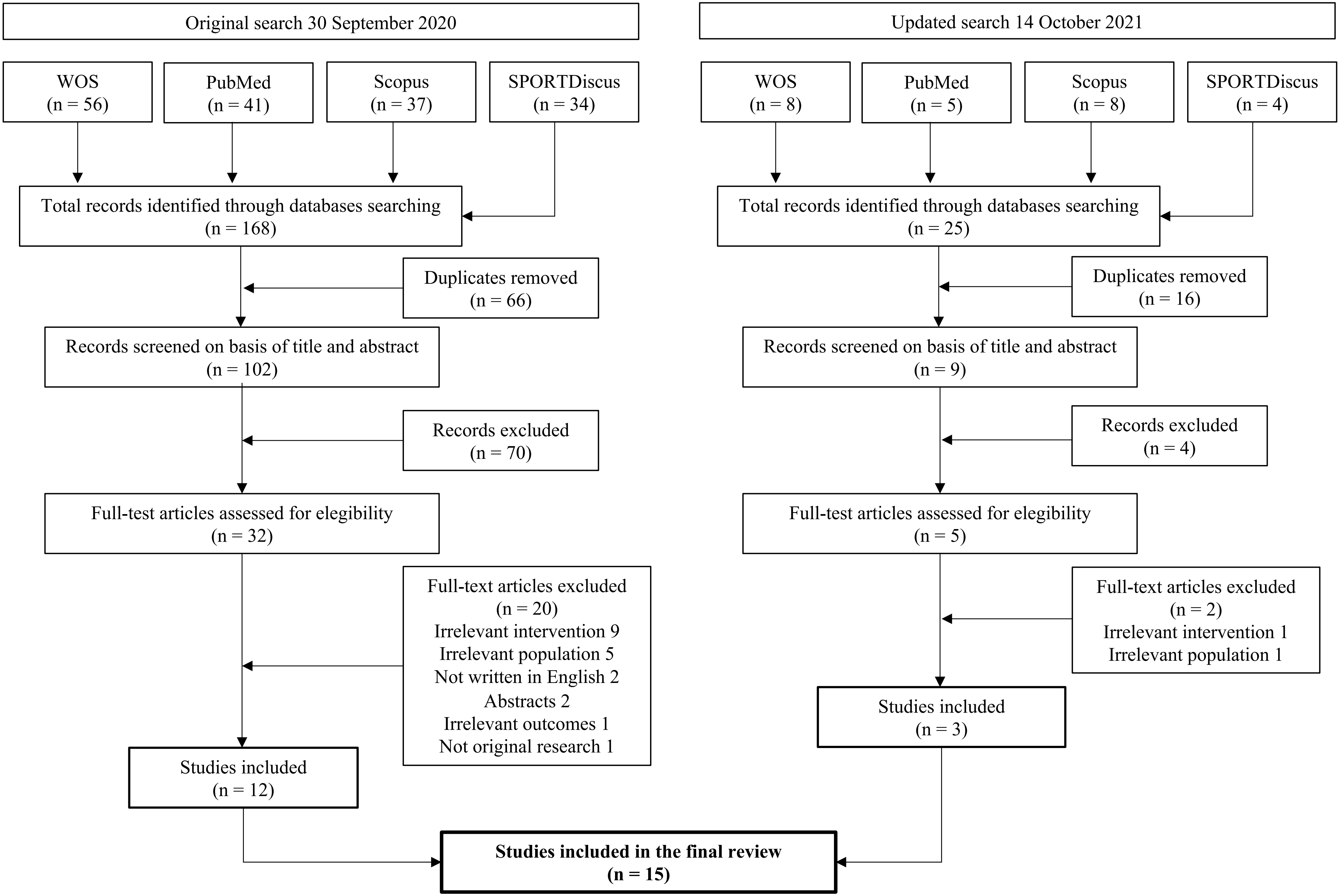
Original search 30 September 2020
WOS (n = 56)
PubMed (n = 41)
Scopus (n = 37)
SPORTDiscus (n = 34)
Total records identified through databases searching (n = 168)
Duplicates removed (n = 66)
Records screened on basis of title and abstract (n = 102)
Records excluded (n = 70)
Full-test articles assessed for elegibility (n = 32)
Full-text articles excluded (n = 20)
Irrelevant intervention 9
Irrelevant population 5
Not written in English 2
Abstracts 2
Irrelevant outcomes 1
Not original research 1
Studies included (n = 12)
Updated search 14 October 2021
WOS (n = 8)
PubMed (n = 5)
Scopus (n = 8)
SPORTDiscus (n = 4)
Total records identified through databases searching (n = 25)
Duplicates removed (n = 16)
Records screened on basis of title and abstract (n = 9)
Records excluded (n = 4)
Full-test articles assessed for elegibility (n = 5)
Full-text articles excluded (n = 2)
Irrelevant intervention 1
Irrelevant population 1
Studies included (n = 3)
Studies included in the final review (n = 15)

Table 1 Definition of the biomechanical swimming terms used in this review

Variable	**Definition**
Angle of attack	Angle of orientation of the axis of the propulsive segment with respect to the tangent of the path of the limb
Body wave velocity	Quantification of the speed of caudal momentum transfer along the body
Co-activation	Simultaneous activation between agonist and antagonist muscles
Distance per kick	Horizontal displacement of the body during one complete kick cycle
Froude efficiency	A dimensionless number, which indicates the proportion of the useful power with respect to the total power, characterized by velocity of displacement, body length, and gravity acceleration
Heaving motion	Vertical, quasi sinusoidal motions produced at the ankle joint during UUS
Kick amplitude	Feet's amplitude
Kick frequency	Number of kicks by unit of time
Kicking symmetry	Production of similar kinematics during the downbeat and upbeat
Pitching motion	The changes in the angle of the feet relative to the water
Pressure drag	The pressure differential between the front and the rear of the body
Strouhal number	A dimensionless number, which represents the ratio of unsteady to steady inertial forces, characterized by the kick amplitude, kick frequency and velocity of displacement
Vortices	Rotating masses of water
Wave drag	The reaction force exerted by the waves, which are created by swimming movements near the water surface

Table 2 Summary of the main purpose, participants background, methodology conducted, and main findings reported of the studies included in this review

Reference	Main purpose	Participants (Age, years) Level	Test	UUS speed (m·s^{-1}) (kick frequency, Hz)	Variables	Main findings
Alves et al. 2007	To analyze the kinematics of UUS in three body positions, prone, dorsal, and lateral	6 NS (17.0 ± 0.3) National	3x25 m UUS (1 prone, 1 lateral, 1 dorsal)	Prone: 1.46 ± 0.15 (2.35 ± 0.27) Lateral 1.27 ± 11 (2.08 ± 0.36) Dorsal 1.42 ± 0.21 (2.30 ± 0.33)	Prone, lateral, and dorsal: Mean velocity (m·s^{-1}) Upbeat mean velocity (m·s^{-1}) Downbeat mean velocity (m·s^{-1}) Kick frequency (Hz) Strouhal number Amplitudes of toes, ankle, knee, hip, shoulder, elbow, wrist, hand, head, and center of mass (m) Peak joint angles of ankle plantar flexion and knee flexion (º) Foot resultant velocity (m·s^{-1}) Upbeat foot resultant velocity (m·s^{-1}) Downbeat foot resultant velocity (m·s^{-1}) Foot resultant acceleration (m·s^{-2}) Upbeat foot resultant acceleration (m·s^{-2}) Downbeat foot resultant acceleration (m·s^{-2})	More ankle, elbow, and center of mass amplitude during lateral kicking compared to prone and dorsal kicking Prone and lateral kicking presented kinematic differences for a similar velocity
Arellano et al. 1999	To find whether the change in body position would affect UUS kinematic variables	11 M (19.9 ± 2.1) International	2x15 m UUS (1 prone 1 dorsal)	Prone 1.68 ± NS (2.21 ± NS) Dorsal 1.67 ± NS (2.24 ± NS)	Downbeat and upbeat duration (s) Kick frequency (Hz) Distance per kick (m) Mean velocity (m·s^{-1}) Body oscillation (º) Downbeat and upbeat: Shoulder, hip, and knee angles (º)	The feet moved vertically during the knee extension and then displayed a curvilinear displacement comprising forward and upward movements Prone and dorsal kicking showed similar downbeat and upbeat duration, kick frequency, distance per kick, and mean velocity Greater shoulder and knee angles in dorsal compared to prone position

					Trunk-horizontal angle (º)	Greater body oscillation in dorsal compared to prone position
Atkinson et al. 2014	To determine how sagittal kick symmetry in UUS between the downbeat and upbeat phases is related to UUS performance	15 M (21.5 ± 3.2) Provincial – international	3x15 m prone UUS	1.64 ± 0.15 (2.11 ± 0.18)	Both upbeat and downbeat: Kick amplitude (m) Kick frequency (Hz) Body length (m) Distance per kick (m) Mean velocity (m·s^{-1}) Mean velocity relative to body length (s^{-1}) Mean and maximum vertical toe velocity (m·s^{-1})	UUS performance correlated to sagittal kick symmetry All swimmers reached high velocities during the downbeat but only the most skillful swimmers reached high velocities during the upbeat
Connaboy et al. 2016	To identify key kinematic determinants of performance for maximal UUS velocity.	8 M 9 F (17.6 ± 1.4) National	3x15 m prone UUS	1.20 ± 0.13 (2.13 ± 0.23)	Maximum velocity (m·s^{-1}) Kick frequency (Hz) Distance per kick (m) Joint ranges of movement of shoulder, hip, knee, and ankle (º) Maximum angular velocities of shoulder, hip, knee, and ankle (º·s^{-1}) Amplitudes of wrist, shoulder, hip, knee, ankle, and 5th metatarsal phalangeal joint (m) Maximum and mean absolute angle of attack of the end-effector (º)	Individual UUS technique was an important predictor of maximum velocity The maximal knee angular velocity correlated with maximal swimming velocity, which emphasizes the importance of a fast knee extension
Crespo et al. 2021	To evaluate the effects of an activation protocol based on PAPE upon UUS	10 M 7 F (16.6 ± 2.0) (15.4 ± 1.8) Competitive	2x10 m prone UUS (1 PAPE 1 control)	M: 1.19 ± 0.12 (2.19 ± 0.38) F: 1.17 ± 0.11 (2.60 ± 0.47)	Push-off velocity (m·s^{-1}) Mean velocity (m·s^{-1}) Mean peak velocity (m·s^{-1}) Mean minimum velocity (m·s^{-1}) Kick frequency (Hz) 10 m time (s)	The 10 m time was reduced after the activation protocol compared to the control condition

Higgs et al. 2017	To determine which kinematic variables of the upbeat and downbeat are related to prone UUS performance	7 M 3 F (21.1 ± 2.6) National	3x20 m prone UUS	1.73 ± 0.31 (NS)	Mean velocity (m·s^{-1}) Both upbeat and downbeat: Kick duration (s) Kick amplitude (m) Peak acceleration (m·s^{-2}) Peak vertical toe velocity (m·s^{-1}) Body wave velocity (m·s^{-1}) Knee and hip peak angular velocity (º·s^{-1}) Knee and hip mean angular velocity (º·s^{-1})	The mean of the peak vertical toe velocities achieved in the upbeat and downbeat (72.3%) and mean body wave velocity (5.2%) explained 77.5% of the UUS performance variance The upbeat speed should be maximized
Houel et al. 2013	To determine the kinematics variables that improve performance during the underwater phase of grab starts	10 NS (21.4 ± 4.5) National	1 grab start	1.76 ± 0.17† (2.32 ± 0.22)	Center of mass mean velocity (m·s^{-1}) Hip mean velocity (m·s^{-1}) Trunk, thigh, leg, and foot angle of attack (º) Kick frequency (Hz) Kick amplitude (m)	Swimmers should maintain a streamlined position until reaching 6 m to avoid hydrodynamic resistance increment Propulsion should be generated only from legs and feet Velocity can be improved by increasing kick frequency while maintaining the kick amplitude
Ikeda et al. 2021	To identify the kinematic variables associated with UUS performance during the acceleration and deceleration phases	9 M (20.4 ± 1.67) Competitive	3–5 × 15m prone UUS	1.75 ± 0.16 (2.37 ± 0.23)	15 m time (s) Kick frequency (Hz) Time of the acceleration phase (s) Time of the deceleration phase (s) Mean velocity (m·s^{-1}) Mean peak velocity (m·s^{-1}) Mean minimum velocity (m·s^{-1}) At maximum and minimum velocity: Shoulder, lower end of the rib, knee, and ankle relative vertical coordinate value and velocity to great trochanter Shoulder, hip, and knee joints, upper trunk, lower trunk, upper leg, and lower leg angular displacement (º) and	Mean horizontal velocity correlated with the angular displacement of the lower trunk in the acceleration and deceleration phases Greater angular displacement of the lower trunk increased angular displacement of the shoulder, knee, and lower leg during the UUS

					angular velocities (º·s^{-1})	
Shimojo et al. 2014	To investigate whether changes in kick frequency would change the other UUS kinematics	10 M (21.3 ± 0.9) National	UUS trials kick frequencies: (85-115%)	1.60 ± 0.12§ (2.26 ± 0.16)	Absolute values and ratio to preferred frequency: Kick frequency (Hz) Non-dimensional kick amplitude (%) Mean velocity (m·s^{-1}) Distance per kick (m) Strouhal number Body wave velocity (m·s^{-1}) Wave length (m) Wave length per body length Froude efficiency First and second upbeat phase (%) Downbeat phase (%)	Kicking at frequencies below the preferred frequency reduced mean velocity Similar mean velocities were obtained when kicking at frequencies above the preferred frequency When kicking at frequencies below the preferred frequency, the distance per kick and amplitude increased Distance per kick, amplitude, and Froude efficiency decreased when kicking at frequencies above the preferred frequency
Shimojo et al. 2019b	To identify the importance of ankle flexibility in UUS	9 M 8 F (19.7 ± 1.1) (19.6 ± 0.8) National	2x20 m 80% kick frequency (1 no ankle restriction 1 ankle restriction)	1.33 ± 0.19§ (1.65 ± 0.18)	Active and passive ankle plantar flexion with and without restriction on land (º) Mean velocity (m·s^{-1}) Kick frequency (Hz) Kick amplitude (m) Froude efficiency Body wave velocity (m·s^{-1}) Maximal and minimal ankle angle (º) Maximal and minimal ankle angular velocity (º·s^{-1})	The restriction of ankle plantar flexion evoked a reduction in mean velocity When restricting the ankle plantar flexion, the ankle internal rotation was reduced
Wadrzykl et al. 2019	To characterize differences in the UUS technique depending on sex	23 M 18 F (16.7 ± 0.6) (16.7 ± 0.5) Competitive	3x7 m UUS	M: 1.35 ± 0.15 (1.85 ± 0.26) F: 1.24 ± 0.12 (1.83 ± 0.20)	Center of mass mean velocity (m·s^{-1}) Maximal flexion and extension of the ankle (º) Range of motion of the ankles and knees (º) Kick frequency (Hz) Kick amplitude (m)	Male swimmers were faster than female swimmers Male swimmers had greater kick amplitude, distance per kick, and product of kick amplitude and kick frequency than female swimmers Female swimmers presented greater

					Distance per kick (m) Downbeat horizontal toe displacement (m) Product of kick amplitude and kick frequency (n)	ankle range of motion than male swimmers Maximal extension of the ankles, distance per kick, and downbeat horizontal toe displacement were positively correlated with mean velocity for both sexes The correlation between the knee range of motion and center of mass mean velocity differed significantly between male and female swimmers
Wadrzyk et al. 2021	To determine whether there are any relationships between somatic build and kinematic indices of UUS	47 M (17.2 ± 1.0) Competitive	3x 12m prone UUS Anthropometric	1.39 ± 0.18 (1.92 ± 0.28)	Mean velocity ($m\cdot s^{-1}$) Kick frequency (Hz) Kick amplitude (m) Distance per kick (m) Product of amplitude and frequency Anthropometric measurements	Somatic build was not related to UUS technique in young male swimmers
Wang et al. 2006	To study the difference in UUS movement between elite and non-elite swimmers	20 NS (22 ± 2.0) (21 ± 1.8) Elite - non-elite	3 UUS trials	Elite 3.34 ± 0.51 (NS) Non-elite 2.10 ± 1.22 (NS)	Mean velocity ($m\cdot s^{-1}$) Mean acceleration ($m\cdot s^{-2}$) Transfer rates of the segmental peak angular velocity Upper trunk, lower trunk, thigh, shank, and foot peak angular velocity ($^{o}\cdot s^{-1}$) between each segment (proximal / distal)	Elite swimmers had higher shank, thigh, and lower trunk peak angular velocity than non-elite swimmers Applying the principle of the kinetic chain, better propulsion was generated as the number of segments involved increased (from upper trunk to feet)
Willems et al. 2014	To investigate the effect of ankle flexibility and muscle strength on UUS performance	15 M 11F (16.4 ± 2.5) National - international	3x10 m UUS 3x10 m UUS ankle restriction Ankle flexibility Ankle isometric strength	1.64 ± 0.20§ (2.08 ± 0.40)	Plantar and dorsal flexors, internal and external rotators isometric strength (N) Active and passive plantar flexion and internal rotation range of motion on land (º) Free and ankle restricted: Mean velocity ($m\cdot s^{-1}$) Kick frequency (Hz)	Positive correlation between mean velocity and isometric strength (normalized by height) of the dorsal flexors and internal rotators The ankle restriction provoked a mean velocity reduction Active and passive ankle plantar flexion on land was associated with ankle plantar flexion during the downbeat

					Distance per kick (m) Ankle plantar flexion, internal rotation, knee, and hip: highest point, maximal flexion point, maximal supination point, and lowest point (º)	The ankle restrictions evoked greater knee flexion
Yamakawa et al. 2017a	To investigate the effects of increased kick frequency on the propelling efficiency and the muscular co-activation during UUS	8 F (20.9 ± 1.9) Competitive	7x15 m prone UUS kick frequencies: (85-115%)	1.35 ± 0.08§ (1.99 ± 0.15)	Kick frequency (m) Kick amplitude (m) Mean velocity ($m \cdot s^{-1}$) Froude efficiency Downbeat kick phase (%) Upbeat kick phase (%) Vertical toe velocity ($m \cdot s^{-1}$) Downbeat mean velocity ($m \cdot s^{-1}$) Downbeat maximum velocity ($m \cdot s^{-1}$) Upbeat mean velocity ($m \cdot s^{-1}$) Upbeat maximum velocity ($m \cdot s^{-1}$) Electromyography of trunk, thigh, and leg muscles	The activation pattern between agonist and antagonist changed from a reciprocal to a co-active pattern as the kick frequency increased Froude efficiency was negatively correlated to the duration of the co-active phase of the trunk muscles Mean velocity was positively correlated to the duration of the co-active phase of the trunk muscles When kicking above the preferred frequency, Froude efficiency was reduced

Abbreviations: M, male; F, females; UUS, undulatory underwater swimming, NS, not stated; PAPE, post-activation performance enhancement.

† Undulatory underwater swimming speed was collected after a start at different distances, only the last speed collected (i.e., less influenced by the dive) is presented.

§ Undulatory underwater swimming speed is only reported for the swimmers' preferred kick frequency or non-restricted condition.

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