Riding to the top – A systematic review on multidimensional performance indicators in surfing

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Abstract
Identifying high-performing and promising athletes is an important task of national surf associations. However, the scientific foundation of performance indicators in surfing has only developed in recent years. This review aimed to (1) find out which performance characteristics discriminate between surfers of different skill levels, and (2) point out gaps in the existing literature and direct future studies by applying the Groningen Sport Talent Model (GSTM) to categorize findings. A systematic review of PubMed, Web of Science, MEDLINE and PsycInfo databases was performed according to the PRISMA guidelines. A total of thirty-one studies were included. Studies were found on anthropometric, physiological, technical, and tactical, but not on psychological characteristics of surfing performance. In total only six studies included female surfers. Findings suggest that a few performance indicators exist in relation to associations between physical capacities and surfing skill. For one, relative arm span seems to be beneficial to surfing performance and discriminates between differently skilled surfers. Additionally, 15 m and 400 m in-water paddle performance, as well as relative upper and lower-body strength also tend to be better in superior surfers. Technical skills, such as the ability to perform aerials and tube rides with a high completion rate, translate directly into an enhanced scoring potential and therefore success in surfing competitions. While a variety of characteristics for high-performance surfing are already indicated, future research needs to focus on developing reliable methods with higher ecological validity to assess these skills. Apart from the in-water paddle tests, most indicators lack a broadly accepted testing method. Especially, the field of psychological skills in surfing should be addressed more in the future.

Keywords
Anthropometry, aquatic sport, in-water paddle testing, relative arm span, strength, talent development, technical skills

“Surfing is a million-dollar thrill, but you learn a nickel at a time. Surfing teaches you patience, and it keeps you learning from the beginning, and then when you get older, you have to learn new ways to handle it all. Life works the same way. Some things take a long time to learn. Other things you already know, but sometimes it takes a while to register.”

Surfing Hall of fame member, Linda Benson, 2016

“Competitive surfing is not only about talented surfing. It’s about the management of your opponent and the management of the waves.”

1988 World Champion, Barton Lynch, 2016

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Introduction

Developing successful athletes is a process that must consider a variety of different variables.\(^3\)–\(^5\) One of the first steps that researchers commonly take, can be seen in identifying important performance characteristics of the respective sport.\(^6\)\(^,\)\(^7\) Based on the identified performance indicators practitioners are able to create performance benchmarks and criteria that ideally help them in identifying and developing future elite athletes. Sports, such as track and field, swimming or cycling usually have clear and objective performance measures which makes it easier to identify talented athletes based on existing performance indicators, compared to more complex domains.\(^8\)\(^–\)\(^10\) Finding such objective and multidimensional performance characteristics is a current challenge for practitioners and researchers in surfing (i.e., wave riding).

In contrast to a lot of popular individual sports, surfing seems to provide bigger challenges to tackle when it comes to identifying the relevant performance influences and indicators. For one, competitions are mostly held in the ocean, leaving athletes exposed to the elements. Hence, surfing performance is strongly influenced by a variety of conditions and environmental factors, such as currents and riptides, wind and weather, and most importantly wave formation and frequency.\(^11\) It is therefore not surprising that competitive surfing has been found to show much larger variability in performance than other individual sports, such as swimming, weightlifting, or running.\(^12\) However, the influence of surfing conditions does not stop the most talented surfers from producing consistently superior performance.\(^13\) In competitions athletes face their opponents in head-to-head matchups, leaving them equally exposed to the same conditions. Therefore, continuous competitive success in surfing, such as the eleven world titles by Kelly Slater, can be explained with the athlete’s skills rather than the environmental influences.

Another difference to many other sports is that the most direct effect on surfers’ competitive success results from only a small part of their in-competition behavior. To advance through the rounds of a contest, surfers must compete against their opponents in several time restricted heats. That is, a head-to-head bout against one, two or occasionally more competitors, which usually lasts between 20–40 minutes.\(^14\) However, much like hunters, surfers spend most of their time during heats trying to bring themselves into the best position to succeed. In fact, during elimination heats (i.e., a heat in which the last placed athletes are eliminated from the contest) professional surfers spend about 51% of the time paddling, 42% percent in a stationary (i.e., waiting) position, while the actual point-scoring activity of wave-riding only accounts for 4% of their activity profile.\(^15\) These three main phases of paddling, waiting (e.g., assessing the approaching waves), and riding the waves are often used to characterize the process of surfing that repeats itself over and over during competitive or recreational surfing sessions.\(^16\) The arguably most crucial part of this cycle can be seen in riding the wave, which starts with a few strong paddle strokes after an appropriate wave has been identified, continues with a take-off from a lying into a standing position on the surfboard and is followed by the ride along the unbroken part of the wave, which is used for maneuvers, such as turns and aerials.\(^16\) Adding to the variability of surfing performance, each of the competitor’s waves are scored by a panel of up to five judges based on their subjective impression of (a) commitment and degree of difficulty, (b) innovative and progressive maneuvers, (c) combination of major maneuvers, (d) variety of maneuvers, and (e) speed, power and flow. Scores per wave can range from 0-10 points, with the two highest-scoring waves comprising the total score of each surfer’s heat.\(^17\)

Considering the wide variety of performance influences, it becomes clear that surfing athletes need an equally diverse set of skills and abilities to succeed in competitions. Consequently, performance relevant factors that have been identified in the literature include physiological characteristics such as good muscular endurance, cardiorespiratory fitness and anaerobic power, mainly in the upper torso,\(^11\) but also excellent balance\(^18\) as well as cognitive and psychological abilities.\(^19\)\(^,\)\(^20\)

The interest in the underlying performance characteristics of surfing has clearly increased over the last fifteen years. While in the early 2000s only a few studies across different academic disciplines existed,\(^11\)\(^,\)\(^21\) the research seems to be evolving in the past years, just like the sport itself. Currently a variety of studies in the field of competitive surfing focus on topics such as performance requirements\(^15\)\(^,\)\(^22\)\(^,\)\(^23\) and scoring criteria,\(^24\)\(^,\)\(^25\) gender specific differences\(^26\)\(^,\)\(^27\) or even how a claim, an excessive celebration of a wave, affects the subjective scoring by the judges.\(^28\) Systematic reviews on load monitoring\(^11\) and on the essential skills of wave-riding\(^29\) can also be found.

However, with the sport having made its Olympic debut in Tokyo 2021,\(^30\)\(^,\)\(^31\) the focus on the high-performance aspect of surfing will most likely grow even further in the future. Especially when considering the importance of well-structured and scientifically based talent programs of the different national surf associations it seems important to identify reliable performance indicators, as they influence how we assess, select, and develop the future elite athletes in this quickly developing sport. To current knowledge, a
few studies on the diverse potential indicators have been performed, yet no systematic review on this topic has ever been conducted.

In order to structure the findings of this review in a systematic manner and allow better insight into discriminating performance characteristics, a theoretical model on talent development will be used as its foundation. Therefore, this review will apply the Groningen Sport Talent Model (GSTM)\textsuperscript{32} (see Figure 1), which is modified after Newell's constraints-led approach\textsuperscript{33} and has been used in systematic reviews with a similar aim in other sports.\textsuperscript{7} The model illustrates how sports performance develops over time based on maturation, learning and training. It includes the contribution of the athlete’s environment (e.g., parents, coaches, club structure, teammates, etc.) and shows how the interplay with the athlete’s multidimensional performance characteristics are related to the task results (e.g., competitive surfing performance).

If we know what variables underpin elite surfing performance, for example through higher wave scores or different skill-levels in surfing, then we can potentially add an important component to the development of guidelines for performance test protocols, as well as for performance benchmarks. This will end up supporting surfing clubs and associations in their endeavor to develop the future World and Olympic surf champions. Hence, it is the aim of this review to find out which performance characteristics discriminate between surfers of different skill levels. Secondly, it applies the GSTM model in a meaningful way to categorize findings, and to point out gaps in the existing literature and direct future studies.

\textbf{Figure 1.} The GSTM as used in Elferink-Gemser and Visscher\textsuperscript{32} (Reproduced by permission of Taylor & Francis Group).
Methods

Study design

This systematic review focusing on performance indicators in competitive surfing was conducted following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) statement.34 This project did not require Institutional Review Board approval and therefore the protocol was not registered prior to its start.

Search strategy & eligibility criteria

To identify relevant articles focusing on Performance Indicators in competitive Surfing, a series of searches of the key databases PubMed (n = 271), Web of Science (n = 621), MEDLINE (n = 208) and PsycInfo (n = 86) were conducted in May 2020. The implemented search strategy of this systematic review is detailed in Table 1, which combined keywords for the category of “surfing”, as well as for the category of “performance”. Additionally, terms related to “sports” in general were also included as a third category, since the terminology of surfing and wave riding seems to be commonly used as a metaphor in other research areas. For similar reasons, phrase searching was applied to the terms “wave riding” and “big wave” by using quotation marks. The three search term categories were applied as keywords or when possible, to all fields of the respective database search engine. The categories were combined using the AND operator.

This review focuses on the performance indicators of competitive surfing and therefore excluded all studies that were using solely recreational or amateur surfers. A comprehensive list of the applied inclusion and exclusion criteria can be found in Table 2. Studies were for example only included if they were written in English and if they focused on comparing ability tests and surf performance, among other criteria. Studies were excluded if they only focused on an intervention or training program to increase surf performance, or if they were dated from before the year 2000 to adjust for the evolution of competitive surfing. Additionally, if the citation of existing articles showed any potential relevance, it was screened at the abstract level. When abstracts indicated potential inclusion, full-text articles were reviewed.

Apart from the database search, articles that were found through a secondary search (i.e., in the reference list of relevant articles) were added to the full-text assessment, if they met the inclusion criteria.

Data extraction

Study selection and the extraction of relevant data was completed by two authors in four phases. First, database searches were exported to the Covidence online software. In a first step the software automatically removed all duplicates from the imported studies. The following step included a screening of all titles and abstracts using the inclusion criteria as a guideline, in order to ex- or include them from the final step, the full-text assessment. During the full-text screening all relevant data was extracted from the included studies to determine the final in- or exclusion of an article.

Quality check

All included studies were assessed independently by two authors for their overall methodological quality based on the “Guidelines for critical review form – Quantitative Studies” by Law et al.35 In case of conflicting scores, a third author assessed the study. All results were discussed among the authors until consensus was reached. The guidelines include 16 items, that aim at objectively assessing the various components of a scientific research article (see supplementary file of this review for details). As was done in two similar reviews by Faber et al.6 and Te Wierike et al.,36 the outcomes of the items were identified as 1, if the criteria was met, and 0 if it was not. Similar to the mentioned reviews a total score (in percentage) was calculated to

Table 1. Detailed search strategy of this systematic review.

| Category       | Keywords                                                                 |
|----------------|--------------------------------------------------------------------------|
| Surfing        | Surfing OR surfer* OR “wave riding” OR “big wave” OR Shortboard OR Longboard OR Surfboard |
| Performance    | Performance OR Physical OR Psychological OR characteristics OR analysis OR Judging OR Improvement OR improving OR increasing OR ability OR skill OR motion OR score OR maneuver OR paddling OR strength OR power OR indicator OR training OR task |
| Sports         | Sport OR sports OR Athletic OR athlete                                    |

Table 2. Eligibility criteria for the review process.

Inclusion criteria:
1. Written in English
2. Studies on Surfing (Wave riding)
3. Participants were surfing athletes
4. Focus on performance indicators
5. Studies between Jan. 2000–May 2020

Exclusion criteria:
1. No direct association of measured variables to differences in competitive surfing level, rating, scores, or success
2. None of the participants were competitive surfers
3. Evaluation of intervention or training program
4. Conference Presentation
5. Focus on injuries
allow for a fair comparison of differently designed studies. Total scores of below 50% were considered as low methodological quality. Good methodological quality was achieved with a total score of 51% to 75%, and the rating of excellent quality for every score above 75%.

Results

Systematic search

The database search, using the described strategy, resulted in 1186 articles. After removal of duplicates (n = 482), as well as an extensive abstract and title screening a total of 84 studies remained. Five further studies were included from the secondary search, which brought the total number of studies for the full-text review to 89 studies. After applying the described in- and exclusion criteria, a further 58 studies were excluded (see Figure 2). After excluding those, thirty-one studies remained of which all met the inclusion criteria. No further studies were excluded during the analysis process. See Figure 2 for the process overview of study selection.

Quality check

The assessment of methodological quality showed a good level among all studies. Fourteen of the included thirty-one studies showed good methodological quality (between 51%–75%). A total of seventeen yielded scores of excellent quality (above 75%). While all studies were consistent across most categories, differences were mainly found in the report of reliability of outcome measures, as well as the acknowledgement of limitations. The overview of the assessment based on the guidelines by Law et al.35 of all included studies can be found in the supplementary information file of this review.

Findings

The included studies were categorized based on the multidimensional performance characteristics outlined in the GSTM. The studies included measurements from four out of the five categories (i.e. Anthropometrics n = 14; Physiological n = 22; Technical n = 5; Tactical n = 3; Psychological n = 0). Across the thirty-one included studies, only one focused entirely on female surfers, while another five included both male and female surfers. The other twenty-five studies included only male athletes. The specific findings are discussed for each category of the GSTM. An overview of the most relevant characteristics for all included studies can be found in Table 3–6.

Anthropometry. – Surfers of varying skill levels were assessed for their anthropometric measurements in fourteen studies. Height, stature, arm span, body
Overview of included studies with main focus on anthropometric characteristics (APM).

| References                      | Participants | Highest surf level | Aim | Relevant measurements | Main findings | Conclusion |
|---------------------------------|--------------|--------------------|-----|-----------------------|---------------|------------|
| Barlow et al.41                  | 79 male surfers | Prof. group: World QS | To relate APM profiles with surf ability. | APM profile (e.g., stature, BMI, skinfolds, girths) and Surf performance (in groups based on season ranking, across groups based on Hutt rating) | Professionals were sig. more mesomorphic and less ectomorphic than intermediates (p < .01). Sign. correlations were found btw. Endomorphy (r = -.366, p ≤ .01), body fat percentage (r = -.268, p < .05), sum of 6 skinfolds (r = -.274, p < .05) and surfing ability across all participants. | Levels of adiposity and muscularity may influence potential for progression between intermediates and professional-level surfing, |
| Coyne et al.3b                   | 29 male surfers | Comp. Group: World CT, World QS, National Level (Australia) | Investigate the relation of APM profile and upper body strength with paddle performance | APM profile (e.g., height, mass, relative arm span, 7 skinfolds); PF: upper body strength (i.e. 1RM Pull-up & Dip) and surfboard paddle performance (i.e. 15m sprint & 400m race) | Sum7, relative arm span & strength were sig. correlated with paddling performances in comp. surfers. Comp. surfers showed sig. advantages in relative arm span (p < .01), sprint (p < .05) and endurance paddle performance (p < .01) | Competitive surfers significantly outperform recreational surfers in endurance paddle performance, which is correlated to body fat and relative arm span. |
| Fernandez-Gamboa et al.41b       | 20 male surfers | Int. Group: World CT, Big Wave World Tour, King of Groms | Comparison of APM and lower body strength to surfer’s ranking position | APM profile (e.g., height, body mass, skinfolds) and PF: lower body strength (i.e., SJ, CMJ, MMP) and surfer’s ranking (based on competition results) | No sign. difference between groups. However, when ranked the higher ranked surfers showed lower skinfolds in some areas, lower sum of skinfolds (p < .05) and higher maximal peak power (SJ: p < .01; CMJ: p < .01) | Moderate to large sig. correlations between surfer’s ranking position and sum of skinfolds and vertical jump show that surfer’s physical performance seems to be accurate indicator of ranking position. |
| Kilduff et al.48                  | 46 male surfers | All participants: World QS | To consider the relationship between 2D:4D ratio and surfing performance | APM profile (i.e., 2D:4D ratio, age, height, mass, surfing years) and surfing ability (i.e. ranking in competition & expert rating) | It was found that right 2D:4D (but not left) was significantly negatively correlated (p = .0001) with coaches rating and competition results | In line with research in other sports, the results suggest that low (right) 2D:4D ratio correlates with high surfing ability in male surfers. |

*World CT (World Championship Tour) can be considered the highest level of professional international surfing. The World QS (World Qualifying Series) can be considered the second highest level of professional international surfing.*

*These studies also include measurements related to physiological factors = PF (e.g., lower/upper body strength and activity profile in a surf competition.*
| References          | Participants                  | Aim                                                                 | Relevant measurements                                                                 | Main findings                                                                 | Conclusion                                                                 |
|---------------------|-------------------------------|----------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Bruton et al.³⁷     | 42 surfers (female n = 21)    | Comp. surfers: State level competitions (NSW, Australia)             | Characterizing movement and neuromuscular properties in high and low-skill surfers     | In males & females lower limb stiffness decreased with increasing surfing experience (p < .05). Leg power was not related to surfing experience. Competitive female surfers used deeper surfing crouch posture and more knee flexion than recreational surfers (p < .05). | For both groups (male & female), more skilled surfers used a greater range of joint movement and a deeper crouch while performing simulated crouch-extension cycles (comparable to movement when generating speed on the wave) |
|                     | Competitive (n = 14)        |                                                                      |                                                                                        |                                                                              |                                                                            |
|                     | Recreational (n = 14)       |                                                                      |                                                                                        |                                                                              |                                                                            |
|                     | Non-Surfer (n = 14)         |                                                                      |                                                                                        |                                                                              |                                                                            |
|                     |                              |                                                                      | **PF:** Crouch and movement test (simulating speed generation on wave), Vertical leg stiffness during hopping, Peak leg press power, Proprioception (during surf-specific crouch) and surfing ability (based on group) |                                                                              |                                                                            |
| Bruton et al.³⁸     | 42 surfers (female n = 21)   | Comp. surfers: State level competitions (NSW, Australia)             | Exploring the role of surf experience/skill in shaping male and female surfers motor skill kinematics during drop landings | Knee flexion and ankle dorsiflexion at initial ground contact were greater in male participants (p < .01), regardless of surf experience. In both sexes, greater range of motion in knee and ankle were related to better level of surfing (p < .01) | The results of the study suggest that males and females use different landing patterns. However, these patterns seem to be influenced by the individual's degree of surfing experience. |
|                     | Competitive (n = 14)        |                                                                      |                                                                                        |                                                                              |                                                                            |
|                     | Recreational (n = 14)       |                                                                      |                                                                                        |                                                                              |                                                                            |
|                     | Non-Surfer (n = 14)         |                                                                      |                                                                                        |                                                                              |                                                                            |
|                     |                              |                                                                      | **PF:** Sagittal plane kinematics and vertical ground reaction force (measured during a laboratory-based 60 cm drop landing task) and surf experience (based on group) |                                                                              |                                                                            |
| Câmara et al.³⁹     | 10 male surfers Age 15–21 years | All participants Competed in the ASP Juniors (now named World CT juniors) | To assess relationship between surfer's upper body aerobic characteristics and their ranking position | Relative W at LT and OBLA were significantly related to ranking position ($r = −.69, p = .02$; $r = −.72, p = .01$, respectively). No sign. relationship found between ranking position and parameters at max. intensity (VO2peak, Wmax, HRmax, Lamax) | The results indicate that surfers with a higher power output (relative to body mass) at intensity of LT and OBLA, have a higher position in the ASP Juniors ranking for European surfers |
|                     |                                |                                                                      |                                                                                        |                                                                              |                                                                            |

(continued)
Table 4. Continued.

| References     | Participants                                                                 | Highest surf level | Aim                                                                 | Relevant measurements                                                                 | Main findings                                                                 | Conclusion                                                                 |
|---------------|-------------------------------------------------------------------------------|--------------------|----------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Chapman et al. | 60 male participants:                                                        | Elite surfers:     | To evaluate adaptations to postural control system by surfing experience | PF: Postural control (assessed in upright bipedal stance using various closed stance positions + different mental tasks, with dependent variables: area of 95th centile ellipse (AoE) and sway path length (SPL); and surfing ability (based on level) | All participants showed systematic increases in SPL and AoE (in tasks EC and ECHB). Expert surfers displayed significantly ($p < .05$) increased SPL but not AoE when sharing attention with both concurrent mental tasks compared with controls | Based on the results of this study standard postural sway indices are not able to show whether surfing experience improves adaptations to the postural control system. However, systematic differences in balance ability between expert surfers and controls might exist |
| Farley et al.  | 20 male surfers                                                               | All participants   | To identify relationships between physiological measures and surfing performance | PF: VO2 peak from incremental ramp test, Anaerobic power from 10-second maximal paddling burst and surfing performance (i.e., season rank NZ) | A significant relationship between anaerobic power and season rank was found ($r = .55$; $p < .05$). However, no significant relationship between season ranks and VO2 peak was found | The findings provide theoretical support for the importance of including anaerobic paddling power in assessments and training protocols of surf athletes |
| Farley et al.  | 59 male surfers                                                               | All participants:  | The purpose of this study was to determine whether the testing procedure of a pool based, 400m endurance time trial | PF: 400m paddle times and average aerobic speed on surfboard in 25m pool. Surf ability: Based on competitive level | 400m paddle times of recreational surfers were significantly slower than all other groups (WCT $p = 0.004$, WQS $p < 0.001$, Junior National Selection $p < 0.001$, Competitive Adult Board-riders $p = 0.001$, Competitive Junior High School competitors $p = 0.001$) | Professional surfers show a greater ability to cover 400 m and generate a higher average aerobic speed compared to lower competitive surfers and recreational surfers |

(continued)
| References                          | Participants | Highest surf level | Aim                                                                 | Relevant measurements                              | Main findings                                                                                     | Conclusion                                                                                     |
|------------------------------------|--------------|-------------------|----------------------------------------------------------------------|---------------------------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Fernandez-Lopez et al.\(^5\)       | 10 male surfers Age 15–21 years Members of Basque Junior team | All participants Competed in the ASP Juniors (now named World CT juniors) | To analyze the association of morphology and a paddling test with ranking position | PF: RHR at lactate threshold, RHR at onset of blood lactate accumulation, Relative power output with max. incremental test) APM profile and surfing performance (i.e. season ranking ASP junior) | Surfers shared a relative short stature and light weight. Relative power output at OBLA was more useful (explained 63.1% of variance) than endomorphy, anthropometric measures and other functional outcomes in predicting ranking position of comp. surfers | Relative power output (at onset of blood lactate accumulation) and endomorphy should be considered important variables in predicting success of young competitive surfers |
| Furness et al.\(^4\)               | 62 male surfers Recreational (n = 47; m age: 26.5 years) Competitive (n = 15; m age: 26.7 years) | Comp. surfers: World CT World QS | To provide a comprehensive physiological profile of competitive and recreational surfers | PF: (e.g., anaerobic: peak power output & velocity on swim bench ergometer; aerobic: VO2 peak uptake through incremental endurance test) APM profile (e.g., height, mass & arm span) and surf level (comp. vs. recreational) | VO2 peak (p < .001) and anaerobic output (M = 303.93 vs. 264.58 W) were both significantly greater in competitive surfers than in recreational surfers. Arm span and total lean muscle mass significantly correlated (p < 0.01) with aerobic and anaerobic performance variables | Key performance variables (i.e. VO2 peak and anaerobic power) are significantly higher in competitive surfer, indicating that this is both an adaption and requirement in this cohort |
| Loveless and Minahan\(^7\)          | 16 junior male surfers Recreational (n = 8) Competitive (n = 8) | Comp. surfers: Members of the Junior National Team (Australia) | To measure and compare peak oxygen uptake and paddling efficiency in recreational and competitive junior male surfers | PF: Paddling efficiency based on VO2 uptake-power output during incremental paddling test (4 stages of 3 min constant load, followed by ramp increase of 20W/30 sec) Surf ability: Based on group (REC vs COMP) | No differences (P > 0.05) were observed for peak oxygen uptake (REC: 2.52 l/min; COMP:2.66 l/min) or efficiency (REC: 248; COMP: 21%). Blood lactate concentration was sign. greater in recreational (2.4 mmol/l) than in competitive surfers (1.6 mmol/l) during submaximal padding. | Peak oxygen uptake and efficiency are not sensitive to differences in surfing ability. Increase in blood lactate concentration in REC compared with COMP suggests that other determinants of paddling endurance, such as blood lactate threshold, might be better at distinguishing surfers of differing ability. |
| References               | Participants                                                                 | Highest surf level | Aim                                                                 | Relevant measurements                                                                 | Main findings                                                                 | Conclusion                                                                 |
|-------------------------|------------------------------------------------------------------------------|--------------------|----------------------------------------------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Lundgren et al.       | 80 surfing participants <18 male (n = 33) >18 male (n = 24) Female (n = 15) Previously injured (n = 8) | All participants: Ranging from World QS to recreational surfers | To describe the ankle ROM among different groups of surfers | PF: Maximum ankle dorsiflexion was measured with a weight bearing knee to wall test (KW) | For the >18 group, the professional surfers had significantly larger weight bearing ankle dorsiflexion ROM measured with KW (p < .05). No difference was found between higher and lower-level surfers in the under 18 group. | Professional surfing athletes have a greater range of dorsiflexion compared to recreational surfers, ball dancers and mixed populations. The KW measure does not discriminate between higher and lower-level adolescent surfers. |
| Mendez-Villanueva et al. | 13 male surfers European Top Level (n = 7; m age: 25.6 years) Regional Level (Spain) (n = 6; m age: 26.5 years) | ETL: ASP – European division | To evaluate and compare upper-body aerobic fitness in competitive surfers with different performance levels | PF: VO2peak, peak power output and lactate threshold in incremental dry-land board paddling test and surf performance (based on season rank) | ELS reached significantly (p < .05) higher values for peak power output and LT4 than RLS. Surf ranking was inversely correlated with peak power output (r = −.65, p = .01) and LT (r = −.58, p = .03) | The findings identify that better surfers have higher upper-body aerobic fitness scores. |
| Minahan et al.       | 16 male junior surfers Competitive (n = 8; m age: 18 years) Recreational (n = 8; m age: 18 years) | Comp. surfers: Australian Junior National Team | Comparing determinants of a 30s all-out paddling effort between junior surfers of different abilities | PF: e.g., Peak sprint power & accumulated O2 deficit in 30s-sprint paddling test; VO2 uptake in incremental-paddling test and surfing ability (based on groups) | Peak sprint power (404 ± 98 vs 292 ± 56 W, respectively, p = .01) and accumulated O2 deficit (1.60 ± 0.31 vs 1.14 ± 0.38L, respectively, p = .02) were greater in competitive surfers, whereas peak O2 uptake was not different. | The higher peak sprint power and larger accumulated O2 deficit in comp surfers suggests that surfing promotes development of anaerobic energy system. Peak sprint power determined during 30-s of sprint paddling might be sensitive measure of surfing ability or experience. |
| References   | Participants                          | Highest surf level | Aim                                                                 | Relevant measurements                                      | Main findings                                                                 | Conclusion                                                                 |
|-------------|---------------------------------------|--------------------|---------------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Paillard et al.\(^\text{18}\) | 17 male surfers: Nat./Intl. level (n = 9; m age: 22.1 yrs) Local level (n = 8; m age: 22-2 yrs) | Not specified any further | To analyze surfer’s postural control and their use of visual information in static and dynamic postures according to surf level | PF: Postural control (i.e., assessed by measuring center of foot pressure with a force platform for 50 s with stable and 25 s with unstable support; eyes open and closed) and Surfing ability based on competition level | In AP posture (instability in the anterior direction), the center of foot pressure (COP) surface presented a group effect (p < 0.0002) a vision effect (p < .00001). In addition, the interaction group x vision was significant (p < 0.01) in the ML posture (instability in the lateral direction) the mean COP velocity presented a group effect (p < 0.01). | The contribution of vision in postural maintenance was less important in Intl. surfers. Intl. surfers had better postural control. The results suggest that expert surfers could shift the sensorimotor dominance from vision to proprioception for postural maintenance. |
| Secomb et al.\(^\text{60}\)  | 18 male surfers m age: 21.2 years | All participants: Competing at an international level (no further details) | Determining whether any sign associations were present between lower-body strength/power, and performance (turning and aerial maneuvers) of elite surfers | PF: e.g., CMJ, SJ and isometric mid-thigh pull IMTP; and surfing performance (based on ranking of turning and aerial maneuvers, judged by Australian Head Coach and Head Judge) | Significant associations were found between ranking of turning maneuvers and peak force in CMJ, SJ and IMTP (r = -0.737, p < 0.01; r = -0.856, p < 0.01; r = -0.683, p < 0.01, respectively), as well as peak velocity and jump height in CMJ (p < .05). No sign. associations for ranking of aerial maneuvers and any variables | The results suggest that surfers who show greater lower-body isometric and dynamic strength and power also perform higher scoring turning maneuvers |
| Sheppard et al.\(^\text{42b}\)  | 20 male competitive surfers Senior (n = 10) Junior (n = 10) | Senior Surfers: Most competed at the World QS | To examine the potential differences in anthropometric characteristics, upper-body strength, and | PF: Sprint Paddling Performance from stationary start to 15 m; APM Profile: Stature, Body Mass, Arm-Span, Sum-7 skinfold, Lean-Mass Ration, IRM Pull UP | Senior surfers were not different from youth surfers for sum-7 skinfold thickness, yet had greater stature (p < 0.001, d = 2.7) and mass (p < 0.001, d = 2.8). Senior surfers | The results suggest that practitioners working with competitive surfers should consider the importance of sprint paddle performance in surfers, and the |

(continued)
| References | Participants | Highest surf level | Aim | Relevant measurements | Main findings | Conclusion |
|------------|--------------|-------------------|-----|-----------------------|---------------|------------|
| Sheppard et al. | 44 male junior surfers | Intl. surfers: World Junior Championships and part of national team programs (Australia) | Developing, refining and evaluating a testing protocol for use with elite surfers, including APM and PF measures | Surf ability. Based on group (Senior vs Junior) | were faster in the 0-15 m sprint-paddle test ($p < 0.001$, $d = 2.9$), possessed higher peak paddling velocity ($p < 0.001$, $d = 2.3$) and had greater absolute 1 RM pull-up strength ($p < 0.001$, $d = 2.8$) | need to optimize lean mass and relative strength, as these factors appear to distinguish between surfers of higher and lower athletic development and competitive level |
| Tran et al. | 32 male junior surfers | All participants: Elite junior surfers who competed in Australian Nationals or World Junior Championships | To determine whether a previously validated testing protocol can differentiate between selected and non-selected surfers. | PF: Power (i.e. CMJ), Strength (i.e. Isometric mid-thigh pull), Paddling performance (i.e. 15 m sprint, 400 m endurance) APM profiles and surfing ability (i.e. based on national team selection status) | There were significant differences ($p < .05$) between S and NS surfers for relative vertical-jump peak force ($d = 9$), CMJ height ($d = 9$), time to 5-, 10-, and 15 m sprint paddle ($d = 8$), sprint paddle peak velocity, time to 400 m ($d = 7$) and endurance paddling velocity ($d = 7$) | All chosen performance variables (i.e. Power, Strength and Paddling Performance) can effectively discriminate between S and NS competitive surfers |

(continued)
| References       | Participants                                      | Highest surf level<sup>a</sup> | Aim                                             | Relevant measurements                                      | Main findings                                                                 | Conclusion                                                                 |
|------------------|---------------------------------------------------|---------------------------------|-------------------------------------------------|-----------------------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Tran et al.<sup>62</sup> | 48 surfers (female <i>n</i> = 15): Senior Elite (SE) (<i>n</i> = 9; m age: 24.5 years); Junior Elite (JE) (<i>n</i> = 22; m age: 16.1 years); Junior Development (JD) (<i>n</i> = 17; m age: 14.7 years) | Not specified any further       | To develop and evaluate a drop-and-stick test method to assess dynamic postural control in differently skilled surfers | PF: Time to stabilization (TTS) and relative peak landing force (rPLF) in a drop-and-stick landing task and surfing ability (based on group) | TTS for the SE (0.69 ± 0.13s) group was significantly (p < .05) lower than for JD (0.85 ± 0.25s). rPLF for the SE (2.7 ± 0.4 body mass; BM) group was significantly lower than the JE (3.8 ± 1.3 BM) and JD (4.0 ± 1.1 BM) | Results suggest that TTS and rPLF in a drop-and-stick landing task can be used as a qualitative measure of dynamic postural control in surfers. |
| Vagheτi et al.<sup>19</sup> | 103 surfers (female <i>n</i> = 11) | Male & Female professionals (male <i>n</i> = 42; Female <i>n</i> = 11; Amateurs <i>n</i> = 25; Practitioners <i>n</i> = 25) | To identify the auditory and visual single span reaction time and surfing ability (based on group) | | | The results suggest that there is a functional (positive) relationship between auditory and visual single reaction span and surf performance. |

<sup>a</sup>World CT (World Championship Tour) can be considered the highest level of professional international surfing. The World QS (World Qualifying Series) can be considered the second highest level of professional international surfing.

<sup>b</sup>These studies also include measurements related to anthropometric measurements = APM.
Table 5. Overview of included studies with main focus on Technical Factors and Scoring Analysis.

| References         | Participants                                      | Highest surf level\(a\) | Aim                                                                 | Relevant measurements                                                                 | Main Findings                                                                                   | Conclusion                                                                                  |
|--------------------|---------------------------------------------------|--------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Ferrier et al\(^{24}\) | 23,631 waves From World CT surfers during 2014, 2015 & 2016 season *no further info on participants | All participants: World CT | To investigate the impact of aerial maneuvers on scoring in professional surfing | Scoring of waves in relation to performance of aerial maneuvers: For each wave surfed, the number of maneuvers were counted and further categorized as either including an aerial (\(n = 2285\)) or non-aerial (\(n = 21,346\)). | A significantly higher score was awarded (\(P = 0.0001\)) when including an aerial in competition across all three seasons. Of the 2285 waves analyzed that included an aerial, 711 aerials were attempted in 2014, 782 were attempted in 2015 and 792 were attempted in 2016. | If a surfer incorporates an aerial maneuver during competition, they will be awarded a significantly higher score. |
| Forsyth et al.\(^{68}\) | 50 male surfers From 11 World CT events during 2015 season (m age 27.8 years) | All participants: World CT | To investigate the influence of turns, tube rides, and aerial maneuvers on the scores awarded | Video recordings from all 11 WCT events were viewed to classify maneuvers performed by the competitors on each wave as turns, tube rides, and aerials. Main effect or interaction of maneuver type or event location on the wave scores was investigated. | There was a significant main effect of both maneuver type (\(P < .001\)) and event location (\(P < .001\)) on score awarded. Waves with at least 1 aerial maneuver were scored on average 1.9 points higher than waves with turns only (\(P < .001\)). Tube rides scored, on average, 0.8 point higher than waves with turns only (\(P < .001\)). | Professional surfers can optimize their potential single-wave scores during competition by successfully completing aerial maneuvers. However, aerial maneuvers continue to be a high-risk maneuver with a significantly lower completion rate. |
| Lundgren et al.\(^{25}\) | World CT surfers from Quarterfinals and up during 2012 season *no further info on participants | All participants: World CT | To provide information on importance, frequency, & completion rates of aerials & tube-rides | Each maneuver was categorized into three broad groups depending on the type of maneuvers: turns, aerials, and tube ride. Waves were analyzed regarding performed. | Aerial maneuver waves and tube rides scored higher with an average wave score of 7.40 ± 1.53 and 6.82 ± 2.13 respectively, compared to other lower risk maneuvers that scored an average of 5.08 ± 2.21 (\(p < 0.001\)). | High performance surfing athletes should be able to execute risk-taking maneuvers in addition to having a high completion rate on traditional maneuvers in competition. |

(continued)
| References          | Participants                                                                 | Highest surf level\(^a\) | Aim                                                                 | Relevant measurements                                                                 | Main Findings                                                                                      | Conclusion                                                                                      |
|--------------------|------------------------------------------------------------------------------|---------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Peirao and Santos\(^{67}\) | World CT surfers from two events during 2007 & 2010 season *no further info on participants | All participants: World CT | To investigate the association between judges’ scores and the variables that represent judging criteria of surfing | Scoring maneuvers had lower completion rate. Significant correlation \((p = 0.05)\) between wave scores and the variables: percentage of maneuvers in the critical section of the wave \((r = 0.68)\), variety of maneuvers \((r = 0.62)\), frequency of carving \((r = 0.51)\), length of ride \((r = 0.76)\) and total frequency of maneuvers \((r = 0.79)\) among others. | All surfing criteria used by judges in this study correlated significantly with scores in the ASP World Tour 2007 and 2010, except for frequency of imbalances in the second competition. |

| Souza et al.\(^{66}\) | World CT surfers from four events during 2009 & 2010 season *no further info on participants | All participants: World CT | To quantify the time taken in the execution of the BT by the athletes and correlate it to the scores awarded | The execution time of each Bottom Turn (BT) for each wave was analyzed. The average BT execution times were correlated with the scores assigned to the respective waves. A significant association was found between the variables BT time and score awarded in 14 of 16 heats analyzed, i.e., in 87.5% of cases. These associations ranged from moderate to very high on the Pearson correlation scale. | The increase of the curve in the base of the wave (BT) can maximize the performance potential in surfing. The BT is a fundamental technical aspect in the construction of subsequent maneuvers that suit the judging criteria. |

\(^a\)World CT (World Championship Tour) can be considered the highest level of professional international surfing.
| References       | Participants                                      | Highest surf level                                                                 | Aim                                                                 | Relevant measurements                                                                 | Main findings                                                                                         | Conclusion                                                                                           |
|------------------|--------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| Barlow et al.    | 51 female surfers                                | All participants: National Level (United Kingdom)                                    | Investigate if APM and activity profiles in female surfers predicts rankings | APM profile (e.g., BMI, skinfold & girth) + activity profile (i.e., GPS in competition) and ranking/result in surf competitions | Sign. correlations (p < .05) were found between national ranking and body fat percentage and several skinfolds. Number of rides, time spent riding, percentage of total distance surfing, and percentage time riding were correlated with placement (p < .05) | Body fat levels were associated with national ranking. The surf related activity levels of the female surfers were sig. related to their competitive success |
| Farley et al.    | 41 male surfers                                  | All participants: National Level (Australia)                                         | Determining the workloads during competitive surfing and investigate differences for locations or heat success | Activity profile of heat winners and heat losers based on GPS and time-motion analysis in competition (i.e., wave count, maximum speed, average speed and total wave distance) | Heat winners showed higher maximal speed (small effect: 0.50 d) and total wave distance (small effect 0.50 d) at the first point break wave location. They also showed higher maximal speed (moderate effect: 0.73 d) and total wave distance (large effect: 1.64 d) at the beach break wave location. Findings were however not significant. | Surfers who placed higher in competition surfer waves longer and at faster speeds, allowing a greater opportunity to perform scoring maneuvers. These results might also suggest a better wave selection by more successful surfers. |
| Furley and Dörre | 76 participants                                   | Expert group: Comp. level not defined, average surfing experience: 10 years         | Investigating the decision-making skills in surfers with different experience | COG variable: Decision-making (indicated via a button press which waves they would try to catch in a computer-based video decision-making task) and surfing ability (based on experience) | Significant main effect of surfing experience on good decisions (p < .01). There was a strong linear trend in the difference between the surfable vs. not surfable wave ratings according to surfing experience (p = .001). | Results suggest that highly experienced surfers possess a cognitive advantage compared to less experienced surfers or a non-surfing control group by being better able to distinguish between surfable and non-surfable waves. |
mass, and skinfold thickness were some of the most commonly assessed variables, all with varying results across the different studies. See Figure 3 for an overview of the assessment instruments in the category of anthropometrics.

While surfers tend to have a relatively short stature and light weight, which has been hypothesized as beneficial, only two of the fourteen studies investigating a relation between height, body mass and surfing ability found significant differences. Not surprisingly those differences were only found between senior and junior surfers in both studies. \(^{41,42}\) In similar fashion senior surfers also showed significantly greater arm span than youth surfers. \(^{42}\) More interestingly, significant differences in absolute and relative arm span were also found when comparing competitive and recreational surfers of similar age. \(^{43,44}\) In swimming greater arm span is associated with enhanced performance, as it enables athletes to move more water and cover longer distances per stroke resulting in higher absolute speed and traction force. \(^{45,46}\) Consequently, both included studies also showed significant correlations between arm span and key performance variables in surfing, such as endurance paddle performance. \(^{43}\) \(\text{VO}_2\) peak uptake and anaerobic power. \(^{44}\) Such variables have an important influence on a surfer’s paddling skill and might thereby contribute to superior surfing performance. Only one of four relevant studies did not find any differences in arm spans between competitive and recreational surfers. \(^{47}\) Contrastingly, no differences between differently skilled surfers were found for relative sitting height, \(^{43,47}\) or for relative biacromial width. \(^{43}\) One study investigated the relation of surfing performance and 2D:4D ratio, which is the ratio of index to ring finger hypothesized as an indicator of prenatal androgen exposure. Kilduff et al. \(^{48}\) found a significant correlation of low 2D:4D ratio in the right hand to expert rating of the elite surfers and their placing in a single World QS competition. Interestingly this finding is in line with suggestions of athletic prowess in other sports. \(^{49}\)

When assessing the somatotype all three studies found that surfers tend to be mesomorphic, as shown for professional senior male surfers\(^{41}\) females\(^{50}\) and junior athletes. \(^{51}\) The measurement of somatotype was able to discriminate between competitive levels, with professional surfers being more mesomorphic and less ectomorphic than intermediate level surfers, \(^{41}\) but not between differently ranked competitive female or junior male athletes from the same level of competition. \(^{50,51}\) A similar trend was observed for girths and bone breadths. Both variables were able to discriminate significantly between professional and intermediate male surfers\(^{41}\) but not between differently ranked female surfers. \(^{50}\)

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**Figure 3.** Overview of assessment instruments of anthropometric measurements in the included studies. Notes: *Only female participants. **Female and Male participants. (Paillard et al., \(^{18}\) Vaghetti et al., \(^{19}\) Furley and Dörr, \(^{20}\) Farley et al., \(^{22}\) Ferrier et al., \(^{24}\) Lundgren et al. (2014), Barlow et al., \(^{41}\) Sheppard et al., \(^{42}\) Coyne et al., \(^{43}\) Furness et al., \(^{44}\) Loveless and Minahan, \(^{47}\) Kilduff et al., \(^{48}\) Barlow et al., \(^{50}\) Fernandez-Lopez et al., \(^{51}\) Sheppard et al., \(^{52}\) Tran et al., \(^{53}\) Mendez-Villanueva et al., \(^{55}\) Farley et al., \(^{56}\) Minahan et al., \(^{57}\) Cámara et al., \(^{37–39}\) Farley et al., \(^{58}\) Secomb et al., \(^{60}\) Fernandez de Gamboa et al., \(^{61}\) Tran et al., \(^{62}\) Lundgren et al., \(^{64}\) Bruton et al., \(^{37}\) Bruton et al., \(^{38}\) Souza et al., \(^{66}\) Peirão and Santos, \(^{67}\) Forsyth et al., \(^{68}\) Chapman et al. \(^{40}\) )
Body fat, lean mass and skinfolds have been investigated by several of the included studies (n = 11), as the body composition seems relevant in an intermittent sport like surfing. Barlow et al.\textsuperscript{41} for example report a significant relation between the rating of a male surfer's ability and their body fat percentage, with better surfers showing lower values. Similar results were found for female surfers regarding their season ranking.\textsuperscript{30} Lean Mass Index was found to successfully discriminate between elite junior surfers and control junior surfers,\textsuperscript{52} selected and non-selected juniors,\textsuperscript{53} as well as between senior and junior competitive surfers.\textsuperscript{42} No significant differences between competitive and recreational surfers were found by only two studies regarding the athlete's body fat\textsuperscript{44} and their Lean Mass Index.\textsuperscript{43} Contrastingly, skinfolds show incoherent results across the different studies.

\textbf{Physiological.} – Surfers of varying performance levels were assessed for their physiological abilities in most included studies (n = 22). VO\textsubscript{2} peak uptake, peak anaerobic power output (W), lower-body strength and jumping abilities were some of the most used assessment instruments. See Figure 4 for an overview of the variables in the category of physiology.

The subcategory of paddling endurance seems to be relevant, when surfers return to the line-up after a long ride or when they adjust their positioning to catch the best waves. Consistently having to compete for a good position in the line-up, surfers may even spend more than half of the total heat time engaging in repeated bouts of high- and low-intensity paddling (i.e., 1–20 seconds), with only short resting periods in between.\textsuperscript{54} A good level of paddling endurance has therefore been argued as an important performance characteristic, which can potentially also reduce fatigue hindering surfing performance towards the end of a heat or competition. Several measurement instruments have been used to assess this ability in the included studies in a laboratory setting. Surprisingly, none of the three studies looking at heart rate (relative and maximal) measures, and only one out of six focusing on VO\textsubscript{2} max values during an incremental ramp test on a modified paddling ergometer were able to discriminate between surfers of varying abilities. Furness et al.\textsuperscript{54} showed VO\textsubscript{2} peak uptake and peak aerobic power (W) both were significantly greater in competitive compared to recreational surfers. Other studies with the same comparison could not find similar results. However, two of those were able to distinguish surfers of different ability based on their lactate threshold at 4 mmol/L\textsuperscript{55} and lactate concentration during submaximal paddling.\textsuperscript{47} Interestingly, especially from a practitioner's point of view, is the strongly cohesive finding that 400 m paddling performance in a pool and on a surfboard can significantly discriminate between competitive and recreational surfers\textsuperscript{43} and between elite juniors and control juniors,\textsuperscript{52} as well as between selected and non-selected junior national team surfers\textsuperscript{53} and between higher level (World CT, World QS and Junior National Team) and lower level surfers.\textsuperscript{56}

Another important factor in surfing performance might be paddling power, which in competition could make the difference between a surfer catching or missing a crucial wave. Even more so, it may enable surfers to have a faster entry into the wave, which will not only improve positioning and velocity for the wave ride, but also allows them to generally catch larger and more critical waves. All these factors result in an opportunity to achieve higher scores, as they directly translate to key components of the judging criteria (i.e., commitment and degree of difficulty, as well as speed, power, and flow). Hence, paddling power is a potential key performance characteristic in surfing. Relevant measures such as the peak anaerobic power output might be helpful in quantifying this skill. While not all studies agree in results, one can observe a tendency. Absolute peak anaerobic output (W) as measured on a paddle ergometer during a variety of sprint paddle tests showed differences between European level junior surfers and regional junior surfers,\textsuperscript{55} as well as between competitive and recreational ones.\textsuperscript{44,57} No differences were found for the latter group by only one study.\textsuperscript{47} Since body mass is a considerable influence on paddling efficiency, the relative peak anaerobic power output could give even more detailed information about a surfer's paddling power. Two studies found a significant correlation of relative anaerobic power and ranking among pro juniors\textsuperscript{39,51} and among the top 35 surfers from New Zealand.\textsuperscript{58} The only study that found no significant relation between ranking and the relative anaerobic power, found that it could very well discriminate between competitive and recreational surfers.\textsuperscript{44} Like for paddle endurance, all studies found cohesive results when assessing paddling power in a setting with higher ecological validity. A 15 m paddling sprint with a surfboard in a swimming pool was able to discriminate significantly between competitive and recreational surfers,\textsuperscript{43} senior and junior surfers,\textsuperscript{42} elite and non-elite juniors,\textsuperscript{52} or even between selected and non-selected junior surfers,\textsuperscript{53} with better surfers paddling faster times. As previously indicated, these results suggest that higher paddling power might enable more successful surfers to catch waves deeper on the peak of the wave and with more entry speed. By doing so they increase their scoring potential on a wave, which could lead to more competitive success.

Upper-body strength, which is hypothesized as a potential influence on paddling power as well as on performance of the pop-up during the take-off phase,
was only assessed by two studies. Coyne et al.\textsuperscript{43} found competitive surfers to be better than recreational surfers in relative dip, but not in relative pull-up strength. Contrastingly, Sheppard et al.\textsuperscript{42} found senior surfers to possess greater absolute and relative pull-up strength than youth surfers. The researchers also found a significant relationship between relative pull-up strength (i.e., 1RM pull-up) and sprint paddling performance (i.e., 5 m, 10 m and 15 m times and velocities), which indicates the usefulness of this variable to surfing performance.\textsuperscript{42} None of the included studies investigated potential differences in isometric or dynamic push-
up strength, which significantly correlated to a quicker pop-up time (i.e., the time it takes a surfer to move from a paddling to a standing position when taking off on a wave) in a later study. A faster pop-up allows a surfer to start riding the wave earlier, thereby maximizing the time in which scoring maneuvers could be performed.

Lower-body strength on the other hand, might have an even more direct influence on competitive status and success in surfing. Being able to apply more force during a turn through greater lower-body strength enables surfers to generate a greater displacement of water, suggesting a more powerful maneuver to judges. One study found significantly higher values of isometric mid-thigh pull strength in elite compared to non-elite juniors, and another higher relative isometric strength in selected compared to non-selected junior surfers. However, the more interesting finding is that performance in counter movement jumps, squat jumps and isometric mid-thigh pull was significantly associated with surfers who performed higher scoring turning maneuvers, which underpins the potential implications for competitive success. However, further associations between measurements of jumping height and competitive level were inconsistent.

In the area of motor control, landing skills and especially postural control appear to be of importance in the sport of surfing. As the athletes move up and down the face of the wave, they must perform a combination of major maneuvers, which they ought to combine with speed, power, and flow in order to get high scores in competitions. Doing so, requires them to consistently remain balanced over the center of their surfboard, absorbing landing forces, even after high aerial maneuvers. Differences in these skills might therefore be expected between surfers of varying performance levels. However, time to stabilization and relative peak landing force during a landing task were only found to differentiate between senior and junior athletes, but not between junior athletes of different competitive levels. Yet, better postural control was suggested in international surfers. Auditory and visual reaction time were also found to be better in superior surfers for both genders. Furthermore, range of motion especially in the ankle has been discussed as important, especially in relation to technical skills and injury prevention. However, the three studies researching the topic come up with contradicting results in relation to differences between skill levels and gender.

Technical. – The technical skills of surfers (i.e., the execution of maneuvers) are crucial as they directly affect competitive success. Although there are a vast number of maneuver variations with different degrees of difficulty, they can be categorized into three groups: Turns, airmans and tube-rides. Turns represent the most fundamental skill, as surfers ride up to the top of the wave, to then turn their surfboard back down with power and skill in a critical section of the wave, from where they continue their ride. For aerial maneuvers, surfers use speed and timing to launch themselves above the wave, then landing in the face of that same wave to continue or finish their scoring attempt. During a tube-ride surfers position themselves inside the breaking wave, aiming to maximize the time inside the barrel (i.e., airspace under the breaking part of the wave), before successfully emerging from it again. The included five studies focusing on technical aspects of superior surfing, analyzed the different maneuvers in relation to the awarded wave scores (see Figure 5).

Souza et al. found a significant relationship between the time taken for a bottom turn and the awarded scores for the respective wave. In surfing, bottom turns are one of the most fundamental maneuvers as they allow a surfer to transition from going down a wave to going back up again. Although they are not directly scored, they precede and prepare critical maneuvers at the top of the wave. Indeed, in fourteen of the sixteen analyzed heats of selected events of the 2009 and 2010 World Tour, the surfers that stayed longer in the bottom turn, therefore covering more area at the base of the wave, were awarded higher scores for the subsequent maneuvers. Doing so, allowed surfers to carry more speed through the slowest part of a wave into the next section, setting a good foundation for high-scoring maneuvers. Furthermore, a draw-out bottom turn also creates a more vertical trajectory that enables the surfers to perform a more critical and powerful top turn. For the Brazilian event of the 2010 ASP season Peirão and Santos found significant correlations between wave scores and total frequency of maneuvers, length of ride and variety of maneuvers among other variables. Interestingly between the 2007 and 2010 season, the number of aerial maneuvers increased from four to twenty-six in the event, a trend that emphasizes the growing importance of these type of maneuvers over the last two decades. This is also confirmed by the number of attempted airmans throughout the WCT season, which increased from 711 in 2014, to 782 in 2015 and to 792 in 2016.

Aerials are seemingly important maneuvers for competitive success in surfing. For example, during the 2015 WCT it was found that waves that included at least one completed aerial maneuver were scored 1.9 points higher than those that only consisted of turns. Ferrier et al. further support those results, in that waves with an aerial maneuver were scored significantly higher than waves without one throughout.
the 2014, 2015 and 2016 WCT season. Tube rides, which are another key maneuver in surfing, were scored 0.8 points higher compared to waves with turns only, in the 2015 WCT season.

68 The same tendency of scoring (i.e., aerials > tube rides > turns) was observed for all final heats (i.e., quarterfinals, semifinals, finals) in the 2014 WCT season.25 Important to note is that Forsyth et al.68 found a main effect not only for maneuver type but also for event location, and therefore the type of wave. Furthermore, the completion rate of high-scoring maneuvers (aerials =~45-55%; tube rides =~60%) was found to be much lower than for low-scoring maneuvers (turns =~90%) throughout the competitive seasons.25,68

**Tactical.** – A total of only three studies focused on tactical components (see Figure 6). For one, Furley and Dörr20 investigated wave selection skills, which is an important part of a surfer’s competitive strategy. Throughout each heat surfers can obtain the so-called priority, which is the unconditional right to choose any wave.17 Only when the surfer with priority exercises this right, is the priority passed on to the next surfer. Therefore, being able to identify the best waves, promises surfers a competitive edge over their opponents, as they can ride the waves with the highest scoring potential while the others cannot. Hence, wave selection seems to be essential to competitive success. When comparing surfers of varying expertise, Furley and Dörr20 indeed found that the participants’ decision making was significantly improved with increased experience. Expert surfers were better at deciding which waves were surfable, and more importantly which ones were not.

Another way of getting information about surfers’ decisions on wave selection and competitive behavior is through their activity profile. While in most cases such information would qualify as a physiological measure, it can also be rated as a tactical instrument that gives great insight into a surfer’s choice of heat strategy. The athletes’ activity profiles might for example reveal whether they were riding as many waves as possible or being very selective. When analyzing the competitive strategies of female surfers, Barlow et al.50 used Global Positioning System (GPS) tracking to find that a variety of variables, such as total time spend riding and total distance surfing and most importantly the total number of rides were significantly correlated with heat placement. The more time a surfer spent sitting the poorer her heat placements was. The results of this study suggested that higher activity, which in this case qualifies as a tactical choice, during a heat can lead to competitive success. However, as suggested by Farley et al.22 the interpretation of GPS data alone is limited, for example because the momentum which is generated during a fall might be recorded as the generated speed on a wave. Therefore, GPS data should always be synchronized with data obtained through additional video recordings (i.e., time-motion analysis), as was done by the second included study focusing on differences in the activity profile of heat winners and losers. Farley et al.22 found that surfers who won their

Figure 5. Overview of assessment instruments of technical measurements in the included studies.
Notes: *Only female participants. “Female and Male participants. (Paillard et al.,18 Vaghetti et al.,19 Furley and Dörr,20 Farley et al.,22 Ferrier et al.,24 Lundgren et al.,25 Barlow et al.,41 Sheppard et al.,42 Coyne et al.,43 Furse et al.,44 Loveless and Minahan,47 Kilduff et al.,48 Barlow et al.,49 Fernandez-Lopez et al.,51 Sheppard et al.,52 Tran et al.,53 Mendez-Villanueva et al.,55 Farley et al.,56 Minahan et al.,57 Câmara et al.,58–60 Farley et al.,60 Secomb et al.,62 Fernandez de Gamboa et al.,64 Tran et al.,62 Lundgren et al.,64 Brunton et al.,68 Souza et al.,66 Peirão and Santos,67 Forsyth et al.,68 Chapman et al.40)
heat (i.e., by placing 1st or 2nd in a heat of four) surfed waves for longer and at higher speeds than those who lost (i.e., by placing 3rd or 4th in a heat of four), in two of three event locations. While higher speed and longer wave rides might indicate better wave selection, it also enables surfers to maximize the scoring potential of a wave by surfing with more speed, power, and flow (i.e., one of the outlined judging criteria).

**Discussion**

The results of this systematic review provide an overview of performance characteristics that discriminate between differently skilled surfers. It also applied the GSTM model to categorize findings, to point out gaps in the literature and direct future research. It is unsurprising that most studies have a strong focus on anthropometric and physiological characteristics. For one, higher relative arm span emerges as a potential influence on surf performance. In theory it allows a surfer to move greater amounts of water per stroke and therefore paddle more efficiently, especially when paired with appropriate levels of physical fitness. The importance of arm span to performance, as well as the correlation to both, VO$_2$ peak uptake and anaerobic power, has also been reported in free-style swimming, a sport that has some important similarities to paddling in surfing. As previously outlined, these factors might contribute to a surfer being able to have a faster entry into the wave and catching them closer to the peak in a more critical section, which can positively influence the scoring potential of a wave. While these findings still need further investigation, relative arm span might be a performance indicator that can be used for talent identification in surfing. However, as with most anthropometric measurements these variables should be seen as performance facilitators rather than determinators.

Considering the increasing homogeneity in anthropometric measures towards elite-sports it is not surprising that somatotype did not show a correlation to ranking position of competitive male and female surfers. However, the finding that professional surfers were more mesomorphic than intermediate level surfers, might allow to see a tendency that somatotype could be a measurement that discriminates between elite and non-elite surfers, but not between ability within a homogeneously high-performing group of athletes. Still, it might be postulated that a more mesomorphic and less endomorphic somatotype is beneficial to surfing performance but might not be a determining variable for talent identification. The same tendency holds true for lean mass and body fat in surfers. Furness et al., p.5 for one suggested that “there is a threshold weight for fat-free mass above which performance enhancements will be hampered. Even if the athlete is very lean” paddling performance might decrease due to the added weight. Similarly, Furness et al. have suggested that not only from a physical but also from an energetical stand-point an extremely low body fat level might not enhance performance in surfing. Therefore, body-fat levels should be within a certain range (e.g., 10.5-22% for male and females based on literature analysis by Furness et al.) but not too high or low.
As in most sports, physiological characteristics of an athlete also play a key role in performance and research of surfing. Yet, across the included studies experimental measurements in those areas were widely inconsistent. One could argue that due to the variety of different set-ups and the novelty of such methods in surfing research, the variable itself might still be relevant as a performance indicator, however the methods would need to be optimized in further research. This also applies to the already promising laboratory measurements such as lactate threshold at 4 mmol/L and blood lactate concentration during submaximal paddling to assess paddling endurance, as well as for the variable of peak anaerobic power output, which might be a good indicator of a surfer’s paddling power.

However, based on the presented findings the most valid measures of paddling power and paddling endurance seems to be the 15 m and 400 m paddling performance in a pool. When discussing the differences between laboratory and in-water settings, Tran et al. for example concluded that “it may be that in-water time trials, rather than dry-land ergometer methods, are required to elucidate truly relevant performance difference in paddling for surfers”. This statement also indicates the variety of influences that affect the paddling performance in-water might get lost on a swim-ergometer, such as pulling technique or hand placement during the stroke. In that matter, while a surfer usually pulls their body over the water surface, during ergometer testing they remain stationary and imitate a movement of pulling the water surface towards them. These remarks point to the fact that in-water testing might show higher ecological validity, a point that should be considered when selecting instruments to identify talents. Therefore, it might be concluded that when assessing aerobic capabilities in surfers, rather than an incremental ramp test with VO2 peak uptake measures, a 400 m endurance paddle test should be conducted by practitioners. Furthermore, it might be advisable that a 15 m sprint paddle test, with additional split times at 5 m and 10 m, can reliably assess paddling power in surfing athletes.

As outlined before, paddling skills are mainly important to bring a surfer in position to achieve competitive success. Points are scored while riding the wave, not paddling on it. For this most crucial part of a competition an athlete’s lower-body strength might be a key-factor. Secomb et al. have indicated that peak force in the counter movement jump, squat jump and isometric mid-thigh pull are strongly associated with the ranking of scores for turning maneuvers. The finding that those measures were also elevated in superior surfers in other studies make a strong case for lower-body strength as a key indicator of competitive success in surfing. As previously outlined, greater lower-body strength might complement technical skills in turn-oriented surfing by generating greater displacement of water, therefore suggesting more powerful maneuvers to the judges.

Furthermore, only few studies have assessed landing skills and postural ability in surfers, with mixed results. Time to stabilization and relative peak landing force during a drop and stick landing task might be an indicator of how well athletes are able to connect major maneuvers on a wave. In combination with lower-body strength (i.e., isometric mid-thigh-pull) and other physical factors, they have also been used to indicate the risk of lower-body injuries in surfing athletes. However, the ecological validity of those measurements should be addressed in future research, especially considering the speed and complexity of the maneuvers that are performed in the critical sections of a wave. Forsyth et al. have recently pointed to a method of how simulated aerial maneuvers on land can replicate the critical features of aerials in the ocean. Such approach might be a more promising assessment method, as important aspects of the criterion movement (i.e., aerial) are included. Being able to assess surfers’ ability to perform aerials safely and at a high completion rate could be valuable to talent identification and development. While traditionally turns and tube-rides used to be the key-elements of successful wave-riding, aerials are now the highest-scoring maneuvers for competitive surfers. Apart from tube-rides, aerials tend to be the only possibility for a surfer to receive a perfect 10 score for a wave, based on a single maneuver, which makes them very desirable in conditions that do not afford a high number of maneuvers. However, as the completion rate for aerials is much lower than for turns, it might be argued that their utility does not only depend on the ability to perform them, but also on strategically calculating the necessity of this high-risk high-reward maneuver.

Despite the significant influence of aerials on heat scores, superior surfers should be well-versed in all technical aspects of surfing. Especially, since different event locations afford different maneuvers. A location-dependency is often reflected in the event-specific scoring criteria outlined by the judges. Therefore, all major maneuvers (i.e., aerials, tube rides, and turns) should be well developed in surfing athletes. This is also relevant for the tactical skills of a surfer, as certain situations might require a variety of lower scoring but highly completable maneuvers. For example, if only a low score is needed to win in the last moments of a heat. However, reliable indicators of those technical abilities are not yet known. A drawn out and extended bottom turn might be one criterion to assess surfers for. This technique is associated with higher scoring turns, as the generated speed and
trajectory allows for greater water displacement in turn-focused surfing. Yet, bottom turns become less relevant in tube riding and aerials, where speed and timing are of more importance.

Not only the performance of quality maneuvers influences competitive success, but also the selection of the right waves. Granted, better surfers seem to be busier during competition, trying to catch more waves than their competition.\textsuperscript{50} However, they also tend to be better at assessing approaching waves and knowing when to take a wave. Interestingly, as pointed out by Furley and Dörr\textsuperscript{20} experienced surfers made significantly better decisions than their less-experienced peers on waves that were unsurfable. This might be a crucial finding in itself, as during heats only the surfer with the “priority right” gets to choose freely which waves they want to surf. Wasting this priority right on a wave with low-scoring potential, could have strong implications for the outcome of a heat. Therefore, assessing wave perception and selection skills in surfers seems important. While both skills will arguably improve with increasing surfing experience, standardized test could be developed through further research, ultimately helping practitioners to assess these skills in talented surfers.

Lastly, although interest in domain-specific research has grown over the last two decades, one area of surfing has not been a focus of recent studies. Based on the categorization through the GSTM and to the best of our knowledge, no study has researched psychological variables in relation to differences in skill-level or competitive success in surfing. Especially when looking at how competitive situations unfold, with time and environmental constrains mixing in a unique way, it will be interesting to see if surfers of different levels can also be discriminated based on these abilities. Especially self-regulatory skills and coping under pressure should be of interest, since surfers consistently must deal with a variety of external influences and an unstable competitive environment.\textsuperscript{74,75} It is therefore encouraged that future research also focuses on the psychological aspects of high-performance surfing.

**Practical implications**

The presented results of this review also have practical implications for surf coaches and associations aiming
to improve their talent programs. As previously outlined, a few methods have been found to discriminate between differently skilled surfers throughout the literature. The different measures seem to be relevant for specific phases of what can be considered the surfing cycle (See Figure 7). Unlike previous literature we suggest a four-phased cycle (instead of three), as a differentiation between the take-off phase and the wave ride seems helpful when assigning the performance indicators.

It may be added that this suggested model is only based on the existing literature and does not claim to be definitive. Arguably there are a variety of factors that are not included yet, such as cognitive ability in assessing the affordances of a wave, which could help to maximize the scoring potential of a given wave. Or psychological components such as self-regulation and intrinsic motivation, which have been discussed as an influence on competitive success in other sports. Therefore, it might be plausible that the same applies to surfing. It is also suggested by the literature that visual-attentional and tactical strategies could greatly influence competitive performance in surfing. Existing or newly found indicators may be adjusted in the model over time.

Limitations

This review also comes with a few limitations. For one, the systematic search for only English databases might have limited the findings. Brazil and Portugal are two countries with active researchers in the field of surfing. It is possible, that relevant literature in the Portuguese language could have contributed to this review. Secondly, by excluding articles that were published earlier than the year 2000, the long-term development of performance indicators in surfing might have been underrepresented. However, it was found to be more important to present a comprehensive review on performance characteristics of modern shortboard surfing.

Conclusion

The findings of this systematic reveal that a few reliable performance indicators could be used for talent identification in surfing. Instruments that keep essential constraints of surfing, such as an in-water paddle endurance (i.e., 400 m) and paddle power (i.e., 15 m) tests show good discriminative power between differently skilled surfers in a variety of studies. Further characteristics of superior surfing performance include the technical ability to perform aerials and tube-riding, among others. While already few indicators for high-performance surfing are known, future research needs to focus on finding reliable and mainly ecologically valid methods to assess these skills. Future research should also focus on the inclusion of female participants and psychological measurements. Both have been widely neglected in current literature.

Key points

- Superior surfers show better performance in 15 m and 400 m in-water paddling tests, and a tendency for a longer relative arm span.
- Upper-body (i.e., relative pull-up strength) and lower-body strength measurements (i.e., isometric mid-thigh pull) may also discriminate better performance in surfing.
- The ability to perform aerials and tube-rides is directly related to competitive success.
- Future research should focus on the inclusion of female surfers, as well as developing reliable instruments with high ecological validity for, amongst other, psychological performance characteristics.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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