

**Stand-up Paddle Boarding:
Muscle activity, kinematics and performance
analysis in recreational athletes**

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Eu, João Diogo Rodrigues Freitas que abaixo assino, estudante com o número de inscrição D2803de Ciências do Desporto da Faculdade de Ciências Sociais e Humanas, declaro ter desenvolvido o presente trabalho e elaborado o presente texto em total consonância com o **Código de Integridades da Universidade da Beira Interior**.

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"The simplicity is the ultimate sophistication."

Leonardo da Vinci

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List of Publications and Communications

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Resumo

Stand-up paddle (SUP) tem vindo a tornar-se cada vez mais popular devido à sua acessibilidade e aos benefícios físicos que proporciona. Apesar de sua crescente popularidade, a literatura é ainda limitada no que se refere aos fatores biomecânicos que influenciam o desempenho no SUP. A presente tese de doutoramento visa preencher esta lacuna, investigando várias determinantes do desempenho no SUP através de quatro estudos. Assim sendo, o objetivo geral foi analisar os fatores cinemáticos e neuromusculares que influenciam o rendimento no SUP, em contexto real, em atletas de nível recreativo. Os seguintes passos foram realizados: (i) revisão de literatura sobre a análise de desempenho no SUP; (ii) análise do comportamento de ativação muscular no SUP, focalizando nos padrões de ativação dos músculos adjacentes e opostos em relação ao lado da pagaiada; (iii) identificação de padrões diferenciadores de desempenho dos praticantes de SUP, com base em variáveis de atividade cinemática e neuromuscular; (iv) análise da influência de diferentes condições externas, como o foco visual, poderão afetar as respostas cinemáticas e neuromusculares durante o SUP. Os principais resultados demonstraram que: (i) atletas de SUP têm mais massa muscular, menos gordura corporal e utilizam técnicas de pagaiada mais eficientes, resultando em melhor desempenho; (ii) parece haver uma maior ativação muscular no lado oposto ao remo no SUP, salientando a importância de alternar o lado da pagaiada para o equilíbrio muscular; (iii) os praticantes mais rápidos mostraram uma maior frequência de pagaiada e uma ativação neuromuscular diferente (i.e., maior atividade do *tríceps braquial*) durante a fase de recuperação da pagaiada; (iv) o foco visual parece impactar significativamente a atividade cinemática e neuromuscular no SUP, sendo que a condição de escolha livre resultou em velocidades superiores, maiores frequências de pagaiada e maior ativação muscular durante as fases de recuperação da pagaiada. Estes resultados demonstram a importância dos fatores cinemáticos e neuromusculares no rendimento do SUP em praticantes de nível recreativo. São assim evidenciadas implicações práticas importantes para os praticantes e treinadores de SUP para a otimização do treino e do rendimento, através de uma melhor compreensão destes fatores influenciadores.

Palavras-chave

Desportos aquáticos, biomecânica, técnica, eletromiografia, desempenho.

Resumo Alargado

Este capítulo resume o trabalho de investigação desenvolvido durante a presente tese de doutoramento intitulada “Stand-up Paddle boarding: muscle activity, kinematics and performance analysis in recreational athletes”. O capítulo inicia com uma introdução geral, destacando as principais questões do estudo e os objetivos gerais e específicos da tese. Em seguida, apresenta-se uma breve descrição dos estudos, incluindo uma revisão da literatura e os estudos experimentais realizados para investigar a atividade neuromuscular e cinemática dos praticantes de stand-up paddle (SUP). O capítulo termina com as considerações gerais da tese e propostas para futuras investigações, destacando as oportunidades para aprofundar o conhecimento sobre a atividade neuromuscular e cinemática nesta modalidade.

Introdução Geral

O SUP começou a ganhar popularidade nos anos 2000, quando surfistas profissionais começaram a usar pagaias enquanto se mantinham de pé em pranchas como uma forma de manter a condição física e as habilidades no surf no oceano (Addison, 2010). O SUP combina elementos do surf e do remo, permitindo que os praticantes remem certas distâncias e/ou surfar ondas (Walker et al., 2010). O SUP é frequentemente descrito como a modalidade aquática que mais cresceu no mundo na última década (Stand Up Paddle Industry Association, 2014; Tsai et al., 2020), tanto como uma atividade recreativa quanto como uma modalidade competitiva (Schram et al., 2016a). No entanto, apesar da crescente popularidade do SUP, a pesquisa científica não acompanhou esse crescimento significativo (Furness et al., 2017).

Os estudos desenvolvidos sobre o SUP até ao momento centraram-se em várias áreas, como biomecânica (Schram et al., 2019), fisiologia (Schram et al., 2016a), epidemiologia (Furness et al., 2017) e psicologia (Schram et al., 2016b). Por exemplo, investigadores tentaram entender a ativação dos músculos *oblíquo externo do abdómen* e *tríceps braquial* ao usar diferentes posturas de deslocamento sobre a prancha (Tsai et al., 2020) e as diferenças cinemáticas entre níveis de desempenho em várias articulações, ângulos e amplitudes de movimento (Banks & Shorter, 2018; Schram et al., 2019). Além disso, estudos avaliaram os níveis de aptidão aeróbia e

anaeróbia de atletas de elite (Neiva et al., 2020; Schram et al., 2016a, b), identificaram lesões comuns e fatores de treino que influenciam seu aparecimento (Castañeda-Babarro et al., 2020; Furness et al., 2017; Waydia & Woodacre, 2016), e determinaram os índices de qualidade de vida associados a atletas de SUP (Schram et al., 2016b, 2017a). Foram ainda apresentados relatórios sobre a representação geográfica e distribuição (Schram & Furness, 2017), personalização de equipamentos (Novak, 2021) ou comportamento em parques e áreas protegidas (Baker et al., 2021). No entanto, torna-se necessário aprofundar estudos que relacionem os parâmetros biomecânicos e fisiológicos usados para descrever a atividade e o comportamento dos praticantes. Neste sentido, esses dados são essenciais para regular a intervenção no treino e competição, fornecendo procedimentos científicos e técnicos, bem como metodologias de análise aplicáveis ao desempenho do SUP (estudo 1).

A ativação e coordenação muscular são cruciais para manter o equilíbrio e a propulsão no SUP. A eletromiografia (EMG) surge como uma ferramenta valiosa para analisar a atividade muscular durante as diferentes fases da pagaiada, fornecendo informações para otimizar a técnica e melhorar o desempenho (Farina, 2006; Vigotsky et al., 2018). A ativação neuromuscular no SUP envolve principalmente os membros superiores, o tronco, os estabilizadores da anca e os joelhos (Ruess et al., 2013; Tsai et al., 2020). Estudos demonstraram que a atividade neuromuscular durante o SUP em água iniciava-se mais cedo e durante mais tempo comparativamente com os ergômetros de simulação laboratorial (Ruess et al., 2013). Para além disso, sabe-se que os praticantes de SUP alternam frequentemente o lado da pagaiada, ajustando a trajetória e o equilíbrio da prancha (Walker et al., 2010). Acresce ainda que as diferentes posições de pagaiada podem influenciar o recrutamento e a ativação muscular (e.g., Tsai et al., 2020). Estes resultados são interessantes, mas devem ser reconhecidas algumas limitações, tais como as amostras de pequena dimensão e falta de utilização de um contexto ecológico. Desta forma, foi nossa intenção colmatar estas lacunas através da análise da atividade muscular durante o SUP num contexto real, considerando o lado da pagaiada e os músculos adjacentes e opostos relativamente à posição do braço (Estudo 2).

Considerando o desempenho em outras atividades similares (Farley et al., 2017) e com base em estudos anteriores (Schram et al., 2019; Castañeda-Babarro et al., 2020), o desempenho no SUP pode ser influenciado por diversos fatores biomecânicos e neuromusculares. Para além da ativação muscular, existem outras variáveis biomecânicas, como a frequência gestual e a distância por pagaiada, que podem ser utilizadas para classificar e determinar os níveis de desempenho no SUP (Neiva et al., 2020). Além disso, a função muscular eficiente durante as diferentes fases da pagaiada

parece ser crucial para a manutenção do desempenho (Hibbert et al., 2023). Assim, torna-se essencial, caracterizar e identificar o desempenho no SUP com base em parâmetros cinemáticos e atividade neuromuscular por meio de análise de clusters. A questão pertinente na pesquisa é a identificação dos parâmetros que influenciam os diferentes níveis de desempenho, um aspeto essencial para otimizar resultados na modalidade. (estudo 3).

Sabemos também que o contexto real da prática de SUP poderá originar diferentes focos de atenção externa que potencialmente poderão influenciar o desempenho dos praticantes. De facto, o foco de atenção poderá desempenhar um papel crítico na manutenção do equilíbrio e da estabilidade durante o SUP. Schram et al. (2016c) conduziram um estudo para avaliar o equilíbrio em atletas de elite de SUP sob diversas condições posturais, inicialmente com os olhos abertos e posteriormente com olhos fechados. O estudo demonstrou que o equilíbrio diminuiu quando a visão e a propriocepção foram comprometidas. De facto, a investigação sugere que a focalização num ponto externo pode aumentar as capacidades motoras e melhorar o desempenho (Wulf, 2007; Stoate & Wulf, 2010). Além disso, num estudo destinado a avaliar a amplitude do tronco em condições de olhos abertos versus olhos fechados, observou-se que o treino de equilíbrio à base de água utilizando SUP poderia ser considerado uma abordagem potencial para melhorar o controlo do equilíbrio em indivíduos mais velhos (Ost et al., 2018). Dada a importância do foco visual na manutenção do equilíbrio, o Estudo 4 pretende examinar a influência de diferentes condições de foco visual no desempenho do SUP. Ao entender como a orientação visual afeta as respostas cinemáticas e neuromusculares, este estudo visa fornecer aplicações práticas para treinamento e otimização de técnicas.

Diante das considerações anteriores, o objetivo geral desta tese de doutoramento foi analisar os fatores cinemáticos e neuromusculares que influenciam o desempenho do SUP, em contextos reais, em atletas de nível recreativo. Para tal, foram desenvolvidos estudos centrados na análise da atividade neuromuscular (EMG) e de parâmetros cinemáticos, diferenciando performances e compreendendo o impacto de diferentes focos de atenção externos. Para atingir esse objetivo geral, definiu-se uma sequência de estudos com os seguintes objetivos específicos:

- Estudo 1: identificar e sintetizar, através de uma revisão sistemática da literatura, os parâmetros externos e internos usados para avaliar o desempenho no SUP e as principais conclusões decorrentes da sua análise.

- Estudo 2: analisar a atividade neuromuscular durante a prática do SUP, considerando o lado da pagaiada e os músculos adjacentes e opostos em relação à posição do braço durante a pagaiada.
- Estudo 3: classificar os praticantes de SUP com recurso análise de clusters de parâmetros cinemáticos e de atividade neuromuscular para diferenciar níveis de desempenho.
- Estudo 4: analisar a cinemática e a atividade neuromuscular no SUP sob diferentes focos de atenção externos, especificamente, comparando três condições: i) olhar para a frente da prancha, ii) olhar para a boia de viragem, ou iii) livre.

Descrição dos Estudos

Estudo 1

Os procedimentos adotados para o estudo seguiram as recomendações PRISMA. Os critérios de inclusão basearam-se em estudos observacionais e transversais que resultaram em dados de desempenho diferenciados, realizados em campo ou laboratório, em indivíduos saudáveis, sem restrições de treino, com idade igual ou superior a 18 anos. A pesquisa baseou-se em estudos originais de quatro bases de dados (Google Scholar, MEDLINE/PubMed, Science Direct e Web of Science) publicados entre janeiro de 1990 e janeiro de 2023. No total, foram incluídos vinte e um estudos. Um total de 238 participantes, de nível competitivo e recreativo, foram avaliados. Os estudos demonstraram que atletas de SUP apresentam maior índice de massa muscular, menor percentual de gordura corporal e adotam técnicas de pagaiada mais eficientes, evidenciando a importância da avaliação do equipamento na melhoria do desempenho desportivo. Parâmetros como o controlo do ritmo são fundamentais para manter a intensidade adequada. A utilização de ergómetros e dispositivos de análise biomecânica e fisiológica auxiliam na compreensão de parâmetros que afetam o desempenho, permitindo a otimização dos equipamentos utilizados em SUP. A tecnologia e a inovação desempenham igualmente, parâmetros importantes no processo de aperfeiçoamento. No que respeita à eletromiografia, somente um estudo comparou a ativação muscular entre as posições distintas de joelhos e de pé. Os resultados demonstraram que a posição de pé apresentou uma ativação mais

significativa dos músculos dos membros inferiores, enquanto a posição de joelhos resultou numa maior ativação do músculo *tibial anterior*.

Os estudos analisados sugerem que os atletas de SUP têm níveis mais elevados de massa muscular e níveis mais baixos de gordura corporal e utilizam uma pagaiada de SUP mais eficiente, o que resulta numa maior eficiência global. Além disso, a avaliação da tecnologia do equipamento de SUP, como pranchas, remos e quilhas, revelou diferenças significativas no desempenho com base no material e no design. No SUP, é importante controlar o ritmo para manter um nível adequado de intensidade durante toda a corrida. A utilização de ergómetros e de dispositivos específicos de análise biomecânica e fisiológica pode ajudar a compreender as variáveis que afetam o desempenho e facilitar a conceção de equipamento para as modificar. Em última análise, estes estudos demonstram o potencial da tecnologia e da inovação para melhorar o desporto do SUP. É de salientar a importância da estabilidade do sistema humano de SUP em diferentes condições de água e a necessidade de mais investigação para melhorar o desempenho e expandir a cultura de experimentação no desporto.

Estudo 2

Catorze praticantes de SUP do género masculino realizaram três percursos de 65 m, nos quais foi registada a eletromiografia de superfície do *trapézio superior*, do *bíceps braquial*, do *tríceps braquial*, do *tibial anterior* e do *gastrocnémio medial* (quatro ciclos de pagaiadas de cada lado). Os dados foram processados de acordo com a percentagem da contração voluntária máxima (% CVM). Os valores de ativação CVM (μV) para cada músculo foram calculados e apresentados como percentagem da CVM (% CVM). A fase de recuperação representou 60% do ciclo de pagaiada, enquanto a fase de tração representou 39%. Durante a pagaiada do lado direito, uma maior % CVM foi encontrada no trapézio superior do lado oposto (24.35%, $p < 0.01$) durante a fase de tração e no bíceps braquial adjacente (8.36%, $p < 0.03$) durante a fase de recuperação. Na pagaiada do lado esquerdo, uma maior % CVM foi encontrada no *trapézio superior* do lado oposto (27.60%, $p < 0.01$) durante a fase de tração e no *tríceps braquial* do lado oposto (42.25%, $p < 0.04$) durante a fase de recuperação. Além disso, a fase de tração apresentou maior % CVM no *trapézio superior* do lado oposto em comparação com a fase de recuperação, tanto na pagaiada do lado direito (24.35%, $p < 0.03$) quanto na pagaiada do lado esquerdo (27.60%, $p < 0.01$). Assim esses resultados ajudam a estabelecer a atividade muscular de ambos os lados da técnica de pagaiada e as diferenças entre os membros superiores e inferiores.

Estudo 3

Um total de catorze praticantes masculinos (24.2 ± 7.1 anos) realizaram três testes submáximos de 65 m. A eletromiografia de superfície foi utilizada para avaliar a atividade muscular, especificamente do *trapézio superior*, *bíceps braquial*, *tríceps braquial*, *tibial anterior* e *gastrocnêmio medial*, em ambos os lados do corpo. A velocidade, frequência de pagaiada (FR), distância por pagaiada (DR) e índice de pagaiada (IR) também foram avaliados. Os clusters foram adequadamente discriminados entre performances de diferentes grupos de acordo com a velocidade. A velocidade ($F = 7.502$, $p = 0.009$, $\eta^2 = 0.73$), o *tríceps braquial* esquerdo durante a puxada direita ($F = 14.160$, $p < 0.001$, $\eta^2 = 0.72$), o *tríceps braquial* direito durante a recuperação direita ($F = 8.076$, $p = 0.007$, $\eta^2 = 0.59$) e o IR ($F = 7.664$, $p = 0.008$, $\eta^2 = 0.47$) foram os principais parâmetros responsáveis pela formação dos clusters. Enquanto os participantes mais rápidos se caracterizavam por altas ativações do *tríceps braquial* direito durante as fases de recuperação à esquerda e à direita, bem como por FR mais elevadas, os participantes com desempenho mais fraco apresentaram baixa ativação dos músculos (por exemplo, *bíceps braquial* e *trapézio superior*). Assim os praticantes que tiveram um melhor desempenho mostraram a maior frequência de pagaiada e maior ativação neuromuscular, especialmente no *tríceps braquial* durante a fase de recuperação, fornecendo uma visão sobre como otimizar o desempenho no SUP.

Estudo 4

Catorze praticantes do gênero masculino realizaram três testes cobrindo 65m, e os parâmetros de EMG e cinemáticos foram analisados em 4 ciclos de pagaiada para os lados esquerdo e direito sob diferentes pontos focais de atenção em três condições distintas: i) olhar para a nose da prancha; ii) olhar para a bóia de retorno; iii) escolha livre. A eletromiografia de superfície do *trapézio superior*, *bíceps braquiais*, *tríceps braquiais*, *tibial anterior* e *gastrocnêmio medial* foram registados. Os dados foram processados de acordo com % MVC (percentagem da contração voluntária máxima). Os parâmetros cinemáticos analisados foram velocidade, frequência de pagaiada, comprimento da pagaiada e índice de pagaiada. Resultados: A condição de escolha livre provou ser a mais rápida, possivelmente devido à maior frequência de pagaiada observada. Além disso, essa condição exibiu maior atividade neuromuscular do *tríceps braquial* direito durante as fases de recuperação à direita e à esquerda. Estes resultados indicam que alguns ajustes no posicionamento da cabeça durante o SUP, visando

otimizar a velocidade ou a participação muscular direcionada, podem ser uma abordagem estratégica para melhorar o desempenho geral.

Conclusão Geral e Futuras Linhas de Investigação

A presente tese centrou-se em diversas variáveis biomecânicas cruciais para compreender o desempenho do SUP. Especificamente, examinámos a velocidade, frequência de pagaiada, comprimento da pagaiada e índice de pagaiada e o sinal electromiográfico dos principais músculos envolvidos no SUP para fornecer uma análise abrangente da forma como estes fatores contribuem para o desempenho. Os nossos resultados realçaram a importância da atividade muscular específica ao longo do ciclo da pagaiada e fornecem orientações para melhorar o desempenho em SUP.

Durante o ciclo de pagaiada, foram encontrados diferentes padrões de ativação muscular entre as fases de puxada e de recuperação da pagaiada, o que realça a necessidade de intervenções de treino específicas para melhorar a coordenação e a eficiência muscular durante estas fases distintas. Os músculos do lado oposto ao da pagaiada apresentaram maior percentagem de atividade muscular do que os músculos do mesmo lado. Em termos práticos este facto sugere que alternar o lado da pagaiada pode ajudar a equilibrar a carga muscular, reduzir a fadiga e evitar lesões, sendo uma recomendação útil para programas de treino de SUP. Na categorização dos praticantes em diferentes grupos com base no desempenho, observou-se que os praticantes mais rápidos usavam uma frequência de pagaiada mais elevada e apresentavam uma ativação neuromuscular diferenciada, particularmente com maior ativação do *tríceps braquial* durante a fase de recuperação. Esses resultados destacam a importância da análise neuromuscular para alcançar melhores performances no SUP. Além disso, verificamos que diferentes condições de foco visual têm um impacto significativo no desempenho do SUP, com a condição de escolha livre a resultar em velocidades mais elevadas, frequências de pagaiada e níveis de ativação muscular superiores. Isto indica que permitir que os atletas escolham o seu foco visual pode otimizar o desempenho.

No seguimento, sugerem-se algumas linhas de investigação a serem exploradas em estudos futuros. Por exemplo, recomenda-se a replicação dos estudos desenvolvidos, mas incluindo uma amostra mais diversificada, com diferentes níveis de experiência e géneros, para obter resultados mais generalizáveis, ou até mesmo diferindo as distâncias, intensidades e contextos. Seria também interessante procurar compreender a resposta neuromuscular e cinemática a diferentes técnicas utilizadas no SUP (i.e., utilização de diferentes posições de colocação da mão ao agarrar o remo) ou analisar os

efeitos da fadiga na cinemática dos praticantes de SUP. Para além disso, devemos integrar mais variáveis e tecnologias mais avançadas para melhor compreender os fatores influenciadores do rendimento, procurando também estabelecer relações entre as variáveis analisadas (e.g., força aplicada e padrão de ativação neuromuscular ao longo da pagaiada). Estes e outros estudos poderão explorar os efeitos e as respostas que poderão ajudar os praticantes e treinadores/professores a otimizar o rendimento, bem como a suportar a expansão da investigação nesta área.

Abstract

Stand-up paddle (SUP) has become increasingly popular due to its accessibility and physical benefits. Despite its growing popularity, there is limited research focusing on the biomechanical factors influencing SUP performance. This doctoral thesis aims to fill this gap by investigating various determinants of SUP performance through four studies. The general objective of this thesis was to analyze kinematic and neuromuscular factors that influence SUP performance in practical contexts, in recreational-level athletes. The following steps were undertaken: (i) a literature review focused on performance analysis in SUP; (ii) analysis of muscle activation behavior in SUP, focusing on the activation patterns of adjacent and opposite muscles relative to the paddling side; (iii) classify SUP practitioners based on kinematic and neuromuscular activity variables and identify performance differentiators; iv) to examine how different visual focus conditions affect kinematic and neuromuscular responses during SUP. The main findings demonstrated that: (i) SUP athletes have more muscle mass, less body fat, and use more efficient paddling techniques, resulting in better performance; (ii) there seems to be higher muscle activation on the opposite side of the paddle in SUP, suggesting the importance of alternating the paddling side for muscular balance; (iii) faster performers showed a higher stroke frequency and different neuromuscular activation (i.e., higher *triceps brachii* activity) during the recovery phase of the stroke; (iv) visual focus significantly impacts kinematic and neuromuscular activity during SUP, with the free choice condition resulting in faster speeds, higher stroke frequencies and higher muscle activation during recovery phases of the stroke. These results demonstrate the importance of kinematic and neuromuscular factors in SUP performance. This thesis provides valuable insights for SUP practitioners and coaches to optimize training and performance through a better understanding of these biomechanical and neuromuscular factors.

Keywords

Watersports, biomechanics, technique, electromyography, performance.

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List of Acronyms

BB	Biceps brachii
BMI	Body mass index
BT	Brachial triceps
Cm.	Centimeters
CV	Critical velocity
DPS	Distance per stroke
EE	Energy expenditure
EMG	Electromyography
FPS	Federação Portuguesa de Surf
g	grams
GPS	Global positioning system
GM	Gastrocnemius medialis
HR	Heart rate
HR _{peak}	Heart Rate peak
HR _{max}	Heart Rate max
Hz	Hertz
ISA	International Surfing Association
m	meters
m/s	meters per second
Kg	Kilograms
Kg/m ²	Kilograms/meters
Km	Kilometers
METS	Metabolic equivalents
%MVC.	Percentage of Maximum voluntary contraction
MVC	Maximum voluntary contraction
OBLA	Onset of blood lactate accumulation
ROM	Range of motion
Rpm	Repetition per minute
s	Seconds
SD	Standard deviation
SPSS	Statistical package for social sciences
sEMG	Surface electromyography
SENIAN	Surface electromyography for the non-invasive assessment of muscles

SF	Stroke frequency
SI	Stroke index
SL	Stroke length
SUP	Stand up paddleboarding
TA	Tibialis anterior
TB	Triceps brachii
TMA	Time motion analysis
UT	Upper trapezius
W	Watts
VE	Ventilation
VO _{2max}	Maximal oxygen uptake

Chapter 1. General Introduction

Stand-up paddleboarding (SUP) is a relatively recent sport and recreational activity that is experiencing a surge in popularity worldwide. SUP combines elements of surfing and paddling, introducing a new dimension to the traditional sport of surfing and making it an attractive option for coastal areas, rivers, or lakes. Its versatility allows for paddling in various conditions, making it a popular choice even on days with calm winds (Burgoyne, 2010). Widely acknowledged as the fastest-growing water sport globally (Stand Up Paddle Industry Association, 2014), the number of SUP participants in the United States increased from 1.1 million in 2010 to 2.8 million in 2014, with a further 26% increase between 2012 and 2015 (The Outdoor Foundation, 2015). In 2011, approximately 1.2 million individuals had their first experience with SUP, reflecting an 18% increase from the previous year (The Outdoor Foundation, 2019). This growing popularity is attributed to its accessible learning curve and diverse physiological and psychological benefits (Schram et al., 2016b; 2017a). SUP, while rooted in surf culture, has expanded to include activities such as fishing, touring, and yoga. This broad appeal has led to significant participation growth over the past two decades, both as a recreational pursuit and a competitive sport (Schram et al., 2016a; Tsai et al., 2020). There is increasing interest among stakeholders across various domains to explore different aspects of SUP through research.

The historical origins of SUP are challenging to pinpoint, as paddling on vessels developed across various cultures from Africa to South America for fishing, transportation, combat, and wave riding. However, the Polynesian islands, particularly Hawaii, have documented the use of boards and paddles since the 18th century through records by Captain James Cook (Marcus, 2015). The practice of standing on a surfboard with a handheld paddle is mentioned as far back as the 1940s when Waikiki beach boys used it to teach surfing. SUP remained relatively unknown until a resurgence in the early 2000s when surfers used paddleboards to stay fit during periods of small waves (Addison, 2010). Today, SUP is described as a recreational activity where the practitioner uses a paddle to navigate through the water while standing on a surfboard (Castañeda-Babarro et al., 2020).

In terms of competition, the first official SUP championship took place in 2004 (Beachboy, 2006), while the inaugural SUP World Championship and International Surfing Association (ISA) event were held in Peru in 2012 after the ISA's institutional

recognition earlier that year (ISA, 2023). In Portugal, the first competition was held in 2010. Competitively, SUP includes various disciplines such as waves, sprint racing (200m and 800m), marathons (crossing/downwind ranging from 8 to 20 km), and technical racing (5 to 6 km). SUP wave competitions follow similar rules to traditional surfing (e.g., scoring is determined by executing maneuvers, generating power and speed, and skillfully navigating), while sprint and marathon races focus on completing distances in the shortest time. In technical racing, participants follow a course distance of 4 to 8 km and are bounded to a maximum board length of 3.81m (ISA, 2022; Schram, 2015). In Portugal, national competitions include SUP waves, technical racing, and marathon disciplines in different board categories (FPS, 2023). Non-competitive variants of SUP include fitness activities, sightseeing, and paddleboard yoga, catering to a range of interests (Tsai et al., 2020).

The body of research developed in SUP remains relatively limited compared to the rapid increase in the sport's popularity observed over the past decade. Studies have primarily focused on anthropometry (Schram et al., 2016a; Castañeda-Babarro et al., 2020), biomechanics (Schram et al., 2019; Tsai et al., 2020), physiology (Schram et al., 2016b; Bakilian et al., 2020), and equipment and race behavior (Dyer, 2018; Dyer, 2021). SUP boards are longer (8-15 feet; 2.44 - 4.57 meters), thicker (4-8 inches; 10.16 - 20.32 centimeters), and wider (26-31 inches; 66.04 - 78.74 centimeters) than traditional surfboards, with practitioners using a long paddle with a single blade to propel themselves through the water (Walker et al., 2010). The paddling technique includes four distinct phases: catch, pull, exit, and the aerial phase (Griffin et al., 2018). The term "catch" describes the entry of the paddle into the water. "Pull" describes when the paddle submerges and drags the water. Finally, the "exit" or recovery occurs when the paddle is taken out of the water to continue the paddling cycle, returning the paddle to the original forward position, ready for the next action. During the pull phase, the force applied by the paddle is greater than the resistance of air and water on the paddler, providing propulsion (Michael et al., 2009). SUP practitioners hold the paddle's handle with the hand opposite to the side they will paddle on, propelling the paddle through the water, and extending the shoulder as well as the trunk. After the catch phase, the practitioner rotates the trunk and pulls themselves forward with the paddle, withdrawing the paddle up to the foot level (Schram, 2015).

SUP, similar to canoeing but done in a standing position, requires rhythmic alternating strokes and isometric contractions of the trunk, glutes, and lower leg muscles to maintain dynamic stability (Schram, 2015). During the pull phase, the force applied by the paddle is greater than the resistance of air and water, providing propulsion

(Michael et al., 2009). It is suggested that a shorter paddle motion, similar to the dragon boat technique, maximizes speed by reducing paddle drag and overall resistance (Ho et al., 2009). The importance of technique in SUP is underscored by the association between suboptimal stroke biomechanics and injuries observed in similar sports like kayaking and outrigger paddling (Hagemann et al., 2004; Schram et al., 2019). Therefore, mastering the proper technique is essential to prevent injuries and enhance performance. Furthermore, understanding the kinematic and neuromuscular aspects is crucial for optimizing performance.

Studies have shown significant differences in stroke mechanics between experienced and inexperienced paddlers (Schram et al., 2019). Inexperienced paddlers demonstrated a greater total shoulder range of motion (ROM) ($78.9^\circ \pm 24.9^\circ$) and less hip ROM ($50.0^\circ \pm 18.5^\circ$) compared to experienced paddlers ($56.6^\circ \pm 17.3^\circ$ and $66.4^\circ \pm 11.8^\circ$ respectively). Additionally, experienced paddlers showed more shoulder motion at the end of the paddle stroke (74.9 ± 16.3 degrees of minimum shoulder flexion) and more elbow extension (6.0 ± 9.2 degrees of minimum elbow flexion) than their inexperienced counterparts (35.2 ± 28.5 and 24.8 ± 13.5 degrees, respectively). These results suggest that experienced paddlers perform a more efficient SUP stroke, possibly due to a larger catch angle and longer stroke length, leading to a higher peak power output. Moreover, differences in paddle frequency and length were observed between elite and recreational or sedentary groups, with elite paddlers achieving higher rates and shorter paddle lengths (Schram et al., 2016c). This underscores the importance of technique understanding performance factors influencing SUP performance.

Discrepancies in performance metrics such as distance covered, stroke rates, and muscle activation patterns across different studies highlight the need for a comprehensive interpretation of results (Schram et al., 2016c; Neiva et al., 2020). In competitive contexts, external variables on race day can significantly impact the distance covered by participants. For instance, in a marathon race, the average distance covered was 13.56 km, with a range of 13.34 to 13.87 km (Schram et al., 2017b). In controlled field tests, participants covered $4,173.8 \pm 241.8$ meters and 3,700 meters during 30 minutes of continuous exercise (Bakilian et al., 2020; Neiva et al., 2020). So, besides the different influencing factors, there are specific contexts that can compromise or potentially increase the performance of SUP participants, and we should further understand this. Therefore, Study 1 of this thesis is dedicated to conducting a systematic review to identify and synthesize external and internal parameters commonly used to evaluate SUP performance under different conditions.

This review aims to establish a comprehensive understanding of the variables affecting SUP performance, providing a foundation for subsequent empirical studies.

Muscle activation and coordination are crucial for maintaining balance and propulsion in SUP. Surface electromyography (sEMG) is a valuable tool for analyzing muscle activity during different phases of the paddle stroke, providing insights into optimizing training techniques and improving performance (Farina, 2006; Vigotsky et al., 2018). Moreover, the comprehensive assessment and feedback provided by sEMG analysis of muscular action allow for the optimization of athletic training and performance (Clarys & Cabri, 1993). Studies by Ruess et al. (2013) and Tsai et al. (2020) have investigated muscle activity in different paddling positions, highlighting the importance of proper muscle recruitment and coordination. While paddling predominantly involves the upper limbs, it also significantly activates the trunk, hip stabilizers, and knee stabilizers (Ruess et al., 2013). Furthermore, muscle activation during field testing began earlier and was sustained longer than during laboratory testing across the catch, power, exit, and recovery phases (Ruess et al., 2013). The participant's position also showed to affect muscle activation (Tsai et al., 2020). For example, In the kneeling position, there was higher activation of the *biceps brachii* muscle compared to the standing position. Conversely, the standing position showed higher activation of the *external oblique* abdominal muscles (Tsai et al., 2020). These findings are interesting but one should acknowledge some limitations, such as small sample sizes and lack of real-life context. This way, we intended to address these gaps by analyzing muscle activity during SUP in a real-life setting, considering the paddling side and the adjacent and opposing muscles relative to arm position (Study 2).

To maintain an ideal posture during paddling, it is necessary to activate and coordinate the muscles of the trunk, upper limbs, glutes, as well as the knee and ankle joints during the movement. This constant activation stimulates balanced proprioceptive receptors, allowing the practitioner to maintain stable paddling even on an unstable board. Continuously and correctly performing the appropriate paddling action while balancing the interference of board buoyancy and blade resistance is challenging. Contraction of the core muscles is essential to establish a stable base for paddling movements, demanding constant muscle activation and sufficient strength to maintain it over time. The goal of SUP is to transfer the force generated by the core to the upper limbs, thereby enhancing propulsion power during paddling (Tsai et al., 2020). Research has begun to emphasize this emerging sport in the last decade (e.g., Schram, 2015), but further understanding is needed.

Considering the performance in other similar activities (Farley et al., 2017) and based on previous studies (Schram et al., 2019; Castañeda-Babarro et al., 2020), performance in SUP can be influenced by several biomechanical and neuromuscular factors. Besides muscle activation, there are other biomechanical variables, such as stroke frequency and distance per stroke, that can be used to classify and determine performance levels in SUP (Neiva et al., 2020). Additionally, efficient muscle function during the pull and recovery phases seemed to be crucial for maintaining performance (Hibbert et al., 2023). To strengthen the knowledge about the factors that can influence SUP performance, we intended to identify the biomechanical determinants by using clustering modeling to categorize performance levels (Study 3). This study builds on the findings of the previous studies, providing a comprehensive view of how different factors interact to influence performance. The insights gained from this study can inform the development of targeted training programs to enhance performance.

The real-life context of SUP practice may contain different focuses of external attention that can potentially influence the practitioners' performance. Attentional focus can play a critical role in maintaining balance and stability during SUP. Schram et al. (2015) conducted a study to assess balance in elite athletes of SUP under various postural conditions, initially with eyes open, and then repeated the tests with eyes closed, the results showed a decrease in balance when vision and proprioception were deprived in certain conditions. Research suggests that focusing on an external point can enhance motor skills and improve performance (Wulf, 2007; Stoate & Wulf, 2010). Furthermore, in a study aimed at assessing trunk amplitude under open versus closed eyes conditions, it was observed that water-based balance training using SUP could be considered a potential approach to enhance balance control in older individuals (Ost et al., 2018). Given the importance of visual focus in maintaining balance, Study 4 of this thesis intends to examine the influence of different visual focus conditions on SUP performance. By understanding how visual focus affects kinematic and neuromuscular responses, this study aims to provide practical insights for training and technique optimization.

The sport of SUP has gained widespread attention, leading to numerous studies aimed at better understanding its movement patterns (Bancks et al., 2018; Praxedes et al., 2019; Schram et al., 2019; Tsai et al., 2020). These studies have highlighted the importance of larger sample sizes and the use of other analyses (e.g., electromyographic and kinetics) to more precisely identify the motor strategies employed during SUP practice (Praxedes et al., 2019). It is important to conduct studies with SUP at the recreational level since the majority of people engage in SUP for approximately 3 hours

per week, for enjoyment and physical conditioning (Schram & Furness 2017). Knowledge of muscle activity patterns and the influence of each side during paddling is still limited and insufficient, and laboratory settings do not fully replicate the real context (Tsai et al., 2020). Similarly, understanding muscle patterns during paddling is crucial, especially in the upper limbs, as they are the segments most recruited in SUP. Thus, the general purpose of this doctoral thesis was to analyze kinematic and neuromuscular factors that influence SUP performance in real-life contexts, in recreational-level athletes. For this, studies were developed focusing on the analysis of muscle activity and kinematic parameters, differentiating performances and understanding the impact of attentional focus, with the following structure:

- Chapter 2 presents a systematic review, identifying and synthesizing the external and internal parameters commonly used to evaluate SUP, under different test conditions and experience levels (Study 1).
- Chapter 3 outlines the experimental studies conducted to achieve the primary objective of this thesis:
 - Study 2 aims to analyze muscle activity during the stroke cycle, considering the paddling side, comparing the opposite and adjacent muscles to the paddle stroke, and examining activation in the upper and lower limbs, to better understand muscle activation patterns during paddling.
 - Study 3 intends to classify SUP practitioners using cluster analysis of kinematic and neuromuscular activity parameters to differentiate performance levels.
 - Study 4 aims to analyze the kinematics and neuromuscular activation in SUP under different external focus (i.e., different visual focus).

Then, after the presentation of the studies, an overall discussion of the findings is provided (Chapter 4), followed by the main conclusions of the thesis (Chapter 5). Additionally, suggestions for future research are presented in Chapter 6.

Chapter 2. Literature Review

Study 1. A Systematic Review for Stand-up Paddle

Abstract

Stand-up Paddle (SUP) combines elements of both kayaking and surfing, allowing for a wide range of activities. Its popularity emerged in the early 21st century with a rapid growth in the number of recreational and competitive practitioners. Performance in SUP is determined by a variety of factors. Despite this, there is a lack of studies that have provided a comprehensive synthesis of all the parameters available in the literature. Therefore, this systematic review aims to identify and synthesize the external and internal parameters commonly used to evaluate SUP performance under different test conditions. The search was conducted in multiple scientific databases (Google Scholar, MEDLINE/(PubMed), Science Direct, and Web of Science) and was completed on January 31, 2022, using the following keywords: “stand up paddle,” “stand up paddling,” and “stand up paddle boarding.” Twenty-one articles were selected, involving a total of 238 subjects at both the competitive and recreational levels. SUP athletes have increased muscle mass, decreased body fat percentage, and used more efficient paddling techniques, highlighting the importance of equipment evaluation in improving athletic performance. More research is needed to improve the performance and expand the culture of SUP. The integration of specific technologies can help to understand better the variables that affect performance outcomes.

Keywords: Anthropometrics, biomechanics, physiology, technology, equipment, paddling

Introduction

The activity of standing up to paddle has been developed in various regions of the world, including South America and Africa. Stand-Up Paddle (SUP), which originated in Hawaii and is also called *Hoe he'e nalu*, involves standing, paddling, and surfing waves (Argley, 2001). SUP gained popularity in the early 2000s when professional surfers began using it to maintain their physical fitness and surfing skills while in the ocean (Addison, 2010). SUP combines elements of kayaking and surfing, allowing practitioners to travel certain distances and/or surf waves (Walker et al., 2010) on boards that are longer, thicker, and wider than traditional surfboards. These features provide better buoyancy, stability, and increased stroke power (Suari et al., 2018).

Over the past decade, SUP has gained recognition as the fastest-growing water sport worldwide, both as a recreational activity and a competitive sport (Stand Up Paddle Industry Association, 2014; Tsai et al., 2020; Schram et al., 2016a). In the United States alone, the number of SUP participants increased from 1.1 million in 2010 to 2.8 million in 2014 (The Outdoor Foundation, 2015), with an additional 26% increase between 2012 and 2015. In 2011, 1.2 million individuals tried SUP for the first time (The Outdoor Foundation, 2015), reflecting an 18% increase from the previous year (The Outdoor Foundation, 2019). Notably, in 2013, SUP had its highest number of first-time participants in the USA. This increasing popularity of the sport has been attributed to its accessible learning curve and multiple physiological and psychological benefits (Schram, Hing & Climstein, 2016a, b; Schram et al., 2017a). A recent systematic review, by Castañeda-Babarro et al., (2022) provided an overview of SUP and confirmed its potential to improve cardiorespiratory fitness, health, and education-related parameters.

However, despite its global appeal, there is currently limited scientific literature available on the performance aspect of SUP (Castañeda-Babarro et al., 2020a). The concept of performance is multidimensional and encompasses the ability to successfully perform a task within a given context, which can be influenced by various physiological capacities such as endurance, strength, speed, or flexibility (Halson, 2014; Mujika, 2017). Due to its complex and multifaceted nature, some authors argue that a single definition cannot fully capture the concept of performance (Portenga et al., 2017).

When analysing individual sports, it is critical to emphasize the technical execution of movements, as well as the biomechanical and physiological parameters that are

essential to provide essential data for adaptive interventions in training and competition, as well as to describe technical performance (Neves et al., 2016). In the context of SUP, it is recognized that performance and success are influenced by a variety of factors. As a result, there is a need for greater precision in the parameters that can describe the activity and behavior of athletes and practitioners, which is essential for practical interventions and the development of the sport. Through scientific and technical methods and applications of analysis, a deeper understanding of SUP performance outcomes can be achieved. Therefore, this systematic review aims to identify and synthesize the external and internal parameters commonly used to evaluate SUP performance.

Materials and methods

The purpose of this study is to summarize the findings and conclusions reported in the literature regarding the performance analysis in SUP using a systematic review that includes practitioners with varying levels of experience. A comprehensive bibliographic search was conducted to identify articles published on this topic. Based on the inclusion and exclusion criteria, some articles were excluded, while others were included in this systematic review.

A comprehensive search of Google Scholar, MEDLINE/(PubMed), Science Direct, and Web of Science databases were performed. The search terms (“stand-up paddle”, “stand up paddling”, “stand-up paddle boarding”, and “SUP”) were used across all fields. There were no restrictions regarding the duration of the study. Articles published in these databases from January 1, 1990, to January 31, 2023, were included.

In terms of inclusion and exclusion procedures, the studies included in this analysis focused on four primary themes. The first was cross-sectional interventions, which are interventions that occur at a single point in time without continuity over time. The second theme includes non-cross-sectional interventions, which have a longer duration and involve continuity over time. The third theme relates to performance outcomes on various SUP tests conducted in the laboratory or in the field. The final subject includes studies in which the participants were healthy individuals without exercise limitations, aged 18 years or older.

Exclusion criteria included dissertations, abstracts and conference proceedings, literature reviews, articles for which the full text was not available, articles not available in English, and articles not published in a peer-reviewed journal.

Studies were included for further analysis if they assessed at least one parameter related to SUP performance. The evidence extracted from the selected studies was based on research design, objectives, subjects, conditions, equipment, procedures/outcomes, and findings.

The assessment of the methodological characteristics of the studies included in this review was carried out by two independent reviewers according to the protocols of the Cochrane Collaboration (Higgins et al., 2019). In cases of disagreement between the reviewers, a third author was appointed to resolve the disagreement. Each included study was assessed for the following dimensions: random sequence generation and allocation concealment (selection bias), blinding of participants and personnel (performance bias), blinding of outcome assessors (detection bias), incomplete outcome data (attrition bias), selective reporting of outcomes (reporting bias), and other sources of bias (Higgins et al., 2011). For each dimension, the assessment was categorized as “high risk,” “low risk” or “unclear risk.” If a clear judgment could not be made due to ambiguity, insufficient clarification, or uncertainty about potential bias, an “unclear risk” designation was assigned.

The search was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). The main outcomes of the studies were identified. Relevant data were extracted and categorized. Data included authors/year, aim, research question, participants, outcomes, and findings. Each of these elements was systematically organized and analyzed independently using Microsoft Excel 2016 software (Microsoft, Redmond, WA, USA).

Results

Figure 1 illustrates the flowchart of the screening process. Initially, the literature search identified a total of 208 articles related to the selected descriptors. However, only 21 studies met all the inclusion criteria and were included in the systematic review. The elimination process included 75 duplicate articles, and 44 studies were excluded based on their titles or abstracts from the remaining 133 articles. After careful assessment of 89 studies for eligibility, 68 studies were excluded because they were classified as

dissertations, conference proceedings, or because the full text was not available on the topic in question. Consequently, the present systematic review includes 21 studies that successfully met the inclusion criteria.

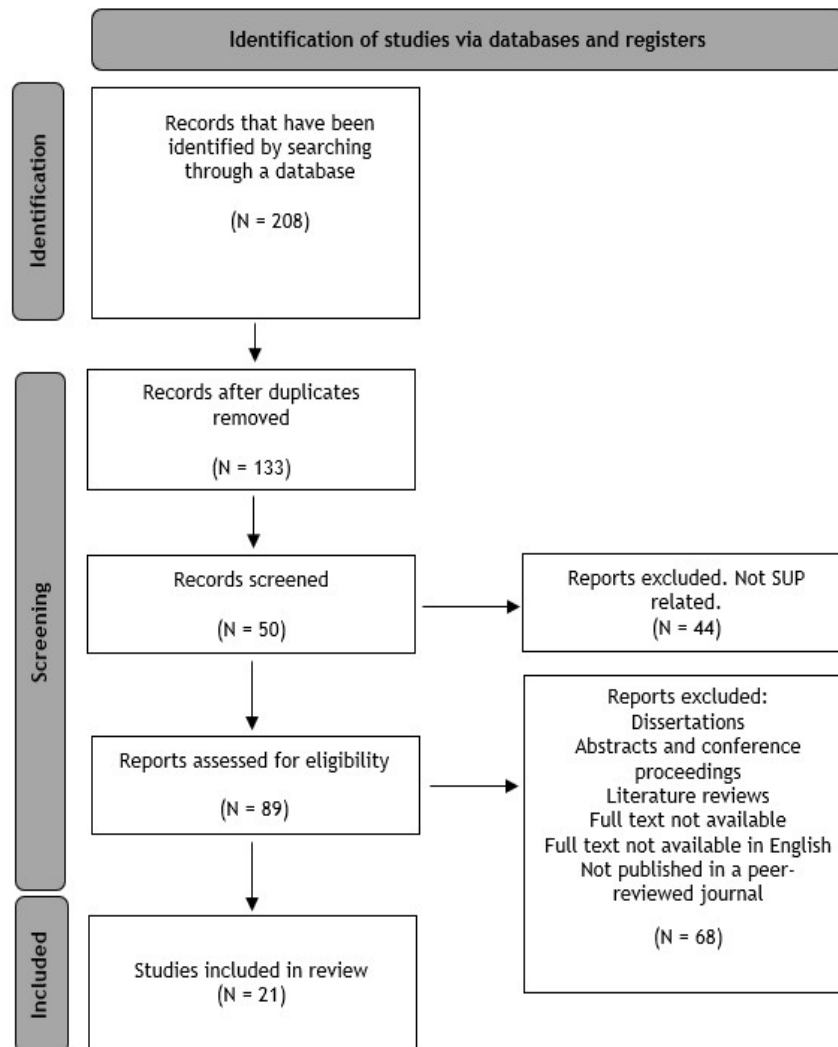


Figure 1 . Flowchart of this systematic review.

In the analysed studies, from different fields such as anthropometry, biomechanics, and physiology, a total of 238 individuals were involved in different exercise protocols performed at different intensities, with different equipment and in different settings. Some studies focused on one gender only, such as (Castañeda-Babarro et al., 2020a; McArthur et al., 2021; Schram et al., 2017a; Suari et al., 2018, while others included both genders, such as Schram et al., 2016a, b, c, 2017a, b; 2019, Ost et al., 2018; Willmott et al., 2020. The technical or performance level varied across studies, including inexperienced participants Schram et al., 2017a, exclusive practitioners in Schram et al., 2019; Tsai et al., 2020; Willmott et al., 2020, competitive/elite

participants Balikian et al., 2020; Castañeda-Babarro et al., 2020a, b; Schram et al., 2014, 2016a, c, 2017a, and a combination of technical levels Schram et al., 2019. The characteristics of the studies are summarized in Table 1.

Table 1. General characteristics of the analyzed studies.

Authors/Year	Title	Area/s	Aim	Participants
Castañeda-Babarro et al., 2020a	Anthropometric profile, body composition, and somatotype in stand-up paddle (SUP) boarding international athletes: a cross-sectional study.	Anthropometry	Describe the anthropometric profile of SUP boarders.	N = 31, males, age, 34.2 ± 12.4 years.
Ost et al., 2017	Improvement of Balance Stability in Older Individuals by On-Water Training.	Biomechanics	Evaluate the effect of SUP practice on upright postural control in older individuals.	N = 16, 9 females, 7 males, 61.68 ± 1.25 years.
Chen et al., 2018	Stability of coupled human and stand-up paddle board.	Biomechanics	Investigate the stability of a stand-up paddleboard.	The system of a rider standing on an SUP is modeled.
Dyer, 2018	A Proposed Field Assessment Method for Stand up Paddle Board Technology.	Biomechanics	Evaluate the intra-test reliability of an outdoor field assessment methodology, and the impact of three different levels of SUP technology on the assessment results.	SUP equipment test.
Schram et al., 2014	Profiling elite Stand-Up Paddle boarders.	Biomechanics Anthropometry	Investigate valid and reliable outcome measures for assessing static and dynamic balance and assess the trunk musculature strength of SUP elite and compared to population mean values.	N=8, 3 females and 5 males, 36.8 ± 6.3 years, and 4.1 ± 2.2 experience years.
Schram et al., 2019	A biomechanical analysis of the stand-up paddle board stroke: a comparative study.	Biomechanics	Comparison between experienced and inexperienced participants in paddle stroke kinematics.	N=26, 7 trained, 3 females and 4 males, 33 ± 7.8 years. 19 recreational, 8 female and 11 male, 24.5 ± 2.4 years.
Tsai et al., 2020	Electromyography Analysis of Muscle Activation During Stand-Up Paddle Boarding: A Comparison of Paddling in Kneeling and Standing Positions.	Biomechanics	Understand the muscle group activation in different paddling postures, kneeling and standing positions.	N=16, college students, recreational, 23.1 ± 1.8 years.
Novak, 2021	A Parametric Method to Customize Surfboard and Stand Up Paddle Board Fins for Additive Manufacturing.	Equipments Computer applications	To provide a fully customizable SUP board fins.	SUP equipment
Schram et al., 2016a	Laboratory- and field-based assessment of maximal aerobic power of elite Stand Up Paddle board athletes.	Physiology Biomechanics	Evaluate athletes in the laboratory and compare with results in the field.	N=10, trained, 4 females and 6 males.

Table 1. General characteristics of the analyzed studies (continued).

Authors/Year	Title	Area/s	Aim	Participants
Schram et al., 2016b	The physiological, musculoskeletal and psychological effects of stand-up paddle boarding.	Physiology Anthropometry Biomechanics	Assess the benefit of SUP on a sedentary group, untrained individuals concerning to balance and strength.	N=13, participants 46.15 ± 11.63 years.
Schram et al., 2016c	Profiling the sport of stand-up paddle boarding.	Physiology Anthropometry Biomechanics	Characterized elite and recreational SUP athletes regarding anthropometry and physiology.	N=45, 2 groups, 5 females and 10 males 15 trained, 15 recreational and 15 sedentary controls.
Schram et al., 2017a	A performance analysis of a Stand-Up Paddle Board marathon race.	Physiology Biomechanics	Analyze performance in a SUP marathon.	N=10, trained, 4 females and 6 males, 34.78 ± 11.49 years.
Schram et al., 2017b	The Long-Term Effects of Stand-up Paddle Boarding: A Case Study.	Physiology Anthropometry Biomechanics	Document the long-term effects of participation in SUP for two individuals.	N=2, middle-aged participants 1 male and 1 female, 58 years.
Suari et al., 2018	The Effect of Environmental Conditions on the Physiological Response during a Stand-Up Paddle Surfing Session.	Physiology	Quantify the physiological demand of an SUP session comparing with traditional surfing, analyze the impact of environmental conditions.	N=1, male, trained, 43 years.
Burgess et al., 2019	Training, Diet and Supplement Regimen of an Elite Female Stand-up Paddler in Preparation for an Ultra-distance Event: a Case Study.	Physiology Anthropometry	Examine the training, diet and supplement regimen of an elite paddler in a race preparation.	N=1, female and 32 years.
Balikian et al., 2020	Anaerobic Threshold in Stand-up Paddle Boarding: Comparison Between Direct and Alternative Methods	Physiology Biomechanics	Compare the AnT evaluated by OBLA to measure the validity of CV and V30min methods.	N=8, trained, 23 ± 3 years.
Castañeda-Babarro et al., 2020b	The Effect of Different Cadence on Paddling Gross Efficiency and Economy in Stand-Up Paddle Boarding.	Physiology Anthropometry	Determine the impact of paddling at different cadences on the movement, gross efficiency, and economy of elite paddlers.	N=10, males, 28.8 ± 11.0 years.
Willmott et al., 2020	The physiological and perceptual responses of stand-up paddle board exercise in a laboratory and field-setting.	Physiology	Quantify and compare the physiological and perceptual responses at 10, 20 and 30 strokes/min in laboratory and field.	N=10, trained, 2 females and 8 males, 23 ± 3 years.
Neiva et al., 2020	A 30-min test applied to stand-up paddleboarding: A pilot study.	Physiology Biomechanics	Analyze performance, biomechanical and physiological variables during a 30 min test.	N=1, male, 28 years and 6 experience years.
McArthur et al., 2021	Effect of Stand-Up Paddle Boarding on Hydration Status in Recreational and Competitive Individuals.	Physiology Anthropometry	To determine the impact of a single SUP session on hydration status, through measurement of nude mass.	N=30, 18 male, 12 female, 45.63 ± 12.44 years and 6.9 ± 4.3 experience years.
Dyer, 2021	Insight into the development and competitiveness of male UK-based Stand-Up Paddleboard flatwater distance racing from 2013 to 2017.	Race behaviour	Investigate the development and behavior of 2 different distance races and determine whether they exhibited different racing behavior.	Male Class.

Fifteen studies examined individuals practicing SUP with anthropometric measurements. Variables such as height, weight, body mass index (BMI), and body fat percentage were the predominant parameters evaluated, with varying results across studies. A comprehensive review of anthropometric assessment is provided in Table 2.

Table 2. Stand up paddle anthropometric studies.

Authors/Year	% Body Fat	BMI (Kg/m ²)	Height (cm)	Weight (kg)	
Schram et al., 2014	Group – 17.5 ± 6.4; Males – 13.4 ± 2.3; Females – 24.4 ± 4.6	24.1 ± 2.3; 24.4 ± 1.6; 23.6 ± 3.7	173.2 ± 5.5; 176.2 ± 3.1; 168.0 ± 4.7	72.3 ± 6.9; 75.8 ± 3.3; 66.4 ± 8.0	
Schram et al., 2016a	Group – 15.87 ± 7.40; Males – 11.13 ± 2.79; Females – 22.98 ± 6.25	24.87 ± 2.42; 25.14 ± 1.36; 24.46 ± 3.77	174.00 ± 0.45; 179.83 ± 6.91; 165.25 ± 4.27	75.59 ± 11.44; 81.32 ± 6.41; 67.00 ± 12.66	
Schram et al., 2016b	Initial test 26.33 ± 5.15; Pre-training 26.74 ± 5.47; Post-training 26.41 ± 5.13	27.98 ± 4.72; 28.17 ± 4.82; 28.02 ± 4.38		84.76 ± 17.22; 85.45 ± 17.96; 84.91 ± 16.51	
Schram et al., 2016c	Elite – 15.5 ± 6.7; Recreational – 20.3 ± 6.9; Sedentary – 27.4 ± 5.6	25.2 ± 2.6; 24.9 ± 2.8; 28.9 ± 5.1	174.3 ± 8.0; 175.1 ± 11.3; 173.2 ± 9.9	76.5 ± 10.6; 76.8 ± 13.1; 86.7 ± 17.3	
Schram et al., 2017b	Male Week 0 – 27.1; Male Week 6 – 27.3; Male Week 52 – 23.7; Female Week 0 – 28.1; Female Week 6 – 25.9; Female Week 52 – 21.5	30.7; 30.4; 28.6	24.8; 24.5; 21.5	Male – 188.8; Female – 152	96.9; 96.1; 90.4; 57.2; 56.7; 53.5
Suari et al., 2018	-	26.6	1.68	76.5	
Burgess et al., 2019	Baseline – 19%; Race Week – 17%	-	-	62.7; 65.0	
Schram et al., 2019	Experienced Inexperienced	-	173.9 ± 50.5 174.1 ± 63.3	76.5 ± 12.2 72.9 ± 11.3	
Balikian et al., 2020	9.4 ± 1.9	-	173.0 ± 9.0	66.9 ± 5.8	
Castañeda-Babarro et al., 2020a	-	23.6 ± 2	175 ± 4.2	74.6 ± 6.6	
Castañeda-Babarro et al., 2020b	12.7 ± 3.9	-	175.4 ± 5.1	74.2 ± 9.4	
Neiva et al., 2020	-	-	1.83	74	
Tsai et al., 2020	-	-	175.22 ± 5.30	70.83 ± 10.58	
Willmott et al., 2020	-	24.3 ± 1.5	170 ± 9	70.5 ± 9.1	
McArthur et al., 2021	-	Group – 24.37 ± 1.9; Males – 24.90 ± 1.7; Females – 23.50 ± 2.1	Group – 1.74 ± 0.09; Males – 1.79 ± 0.08; Females – 1.67 ± 0.05	Group – 75.11 ± 11.52; Males – 80.66 ± 10.27; Females – 65.75 ± 6.33	

A selection of ten studies in the field of biomechanics was analysed. These studies examined a number of facets, including postural control, physical performance, muscle activity, body balance, and technology assessment. A comprehensive summary of the results derived from these studies is presented in Table 3.

Table 3. Stand Up paddle Biomechanics studies.

Authors/Year	Protocol	Findings
Schram et al., 2014	Tests via ultrasound (cross-section of the multifidus). Postural control tests. Lumbar extension isometric test.	Greater levels of dynamic postural control indicated by reduced, velocity of sway in comparison to local and national level surfers.
Schram et al., 2016a	Laboratory test, progressive VO ₂ max ergometer protocol beginning at 5 W with an increase of 5 W every minute until individual burnout. Field test, Progressive VO ₂ max starting at 30 strokes/min and increasing cadence by 5 strokes/min each min, until individual burnout.	A significant difference was found in peak speed measured in the field (+42.39%) compared with in the laboratory.
Schram et al., 2016b	Laboratory test, the ergometer VO ₂ max protocol began at an initial of 5 W with a 2 W increase each minute until volitional exhaustion. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	Peak speed increased 15.79 % and distance covered in 10 s increased 12.37 %.
Schram et al., 2016c	Laboratory test, progressive VO ₂ max ergometer protocol beginning at 5 W with an increase of 5 W every minute until individual burnout. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	The elite group displayed better results in both aerobic and anaerobic tests in terms peak stroke rate, distance covered, and peak speed compared to the recreational and sedentary groups.
Schram et al., 2017b	Analyze the performance in a SUP marathon.	Range of distance (13.3-13.9 km) and peak speed (18.8-26.4 km/h).
Chen et al., 2018	The system of a rider standing on a SUP paddleboard was modeled as a planar motion of a buoyant body with a rectangular cross-section, with an added mass attached at a fixed height.	The eigenvalue contours are in good agreement with qualitative terms such as beginner and professional. The analytical results of the rectangular board show the same trend as the experimental results from a real SUP product.
Dyer, 2018	One participant completed a series of randomized runs at 2.5 m/s over a distance of 230 meters in three separate test events, all held at a flat-water test venue.	The proposed assessment method is recommended as a specific, geographically accessible, and cost-effective means of evaluating SUP technology.
Ost et al., 2018	Performing the tandem Romberg posture (heel-to-toe). Body balance tested in a tiptoes posture, with the ankles in full plantar flexion and keeping the feet barely hip width apart. Both postures were evaluated for a time interval of 30 seconds.	Reduction in anteroposterior and mediolateral amplitudes of body sway in both visual conditions, while walking had no effect on balance.
Schram et al., 2019	Laboratory test, 2 successive paddling attempts (both sides), in a randomized predetermined fashion during 40 s keeping a power of 20 W.	Greater overall shoulder ROM and less hip ROM for inexperienced and shoulder motion at the end of the paddle stroke and more extension at the elbow for the experienced ones.
Tsai et al., 2019	Field tests in an outdoor pool, the participants replicated paddling at a comfortable speed in a standing position (2 times) and kneeling (1 time) alternating sides after 3 strokes.	Biceps showed continuous activation in the pull phase and higher when kneeling. Peak muscle activity of the external oblique of the abdomen and triceps were higher in standing. Gastrocnemius was activated to maintain stability.
Bakilian et al., 2020	Field test, 3 maximal efforts at 400, 500 and 800m; 3 efforts at 85, 90, and 100% of maximal 500m and a 30- minute continuous effort.	The maximal efforts of 400, 500, and 800m took 153.8 ± 14.6 , 194.3 ± 18 , and 319.3 ± 25.8 seconds, respectively. The relationship between distance and time showed high levels of linearity. The total distance covered during the 30-minute effort was $4,173.8 \pm 241.8$ m.
Neiva et al., 2020	Field test, in calm water, a 30-minute continuous test.	3700m performed at 2.19 ± 0.32 m. s ⁻¹ , 52.63 ± 2.62 strokes/min, and 2.39 ± 0.39 m per stroke.

A selection of nine studies examined heart rate (HR) responses, aerobic and anaerobic performance, and physiological demands associated with SUP under a variety of conditions, including exercise protocols, stroke rates, and participant characteristics. A summary is provided in Table 4.

Table 4. Stand Up Paddle heart rate measure.

Authors/Year	Protocol	Findings
Schram et al., 2016a	Laboratory test, progressive VO_{2max} ergometer protocol beginning at 5 W with an increase of 5 W every minute until individual burnout. Field test, Progressive VO_{2max} starting at 30 strokes/min and increasing cadence by 5 strokes/min each min, until individual burnout.	HR mean b·min ⁻¹ $1/HR_{max}$ Laboratory - 180.9 ± 15.58 Field - 183 ± 9.89
Schram et al., 2016b	Laboratory test, the ergometer VO_{2max} protocol began at an initial of 5 W with a 2 W increase each minute until volitional exhaustion. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	Initial test - 171.46 ± 16.72 Pre-training - 172.31 ± 16.10 Post training - 171.23 ± 15.14
Schram et al., 2016c	Laboratory test, progressive VO_{2max} ergometer protocol beginning at 5 W with an increase of 5 W every minute until individual burnout. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	Predicted HR_{max} Elite - 102.7% Recreational - 103.9% Sedentary - 98.0% Elite - 186.60 ± 15.00 Recreational - 187.6 ± 13.71 Sedentary - 173.93 ± 17.21
Schram et al., 2017a	12.7 km, a 0.89m low tide, 11 knot northerly wind with 14 knot gusts, 0.5 m of swell with a 5 sec wave period at the beginning of the endurance run.	Group - 168.56 ± 9.79 Males - 172.00 ± 10.32 Females - 161.67 ± 3.21 Group - 187.00 ± 13.52 Males - 194.17 ± 9.87 Females - 172.67 ± 5.03
Suari et al., 2018	10 sessions analyzed, 14.9 hours duration. Preceding to the sessions, 2 maximum aerobic tests were performed, first in a bicycle ergometer and after a week on a manual ergometer.	53% of the sessions, the HR was maintained between 60% and 80% of the HR_{max} . 47% of the sessions, the HR exceeded 80% of HR_{max} . In 18% of the sessions, the HR exceeded 90% of HR_{max} . Quick Fall and Long Fall, median of 155 and 154 bpm, 85.0% and 85.5% HR_{max} . Riding waves, 152 bpm, 83.9% HR_{max} . Paddling to Peak, 150 bpm, 82.7% bpm. General Paddling, 139 bpm, 76.8% HR_{max} .
Castañeda-Babarro et al., 2020b	Firstly incremental exercise test was conducted to assess maximal oxygen uptake and peak power output (PPO). Second test, 3 trials of 8 min each at 75% of PPO reached in the first test session. Three cadences were carried out in different trials randomly assigned between 45–55 and 65 strokes·min ⁻¹ (spm).	HR_{max} 183.2 ± 14.1 Range - 164 - 207
Neiva et al., 2020	Field test, in calm water, a 30-minute continuous test.	160.78 ± 3.18 bpm Predicted HR_{max} - 85.34%.
Willmott et al., 2020	Laboratory test, VO_{2peak} ergometer, outset at 20 strokes min ⁻¹ and afterwards growing at 3 strokes min ⁻¹ until individual burnout. Incremental SUP trials - Paddled for 5-min at stroke rates of 10, 20 and 30 strokes min ⁻¹ . Field tests - Paddled for 10, 20 and 30 strokes min ⁻¹ for 5-min per step.	Laboratory - 5min - 105 ± 8, 10min - 128 ± 13, 15min - 155 ± 17. Field - 5min - 107 ± 17, 10 min 121 ± 14, 15min - 136 ± 18. VO_{2peak} SUP test - Max HR - 186 ± 8

Table 4. Stand Up Paddle heart rate measure (continued).

Authors/Year	Protocol	Findings	
McArthur et al., 2021	In a cross-sectional study, heart rate (HR) was monitored throughout the SUP session using a telemetry HR monitor watch and chest strap, with both average and peak HR, and duration being recorded.	Group - 135 ± 20.3 Males - 140 ± 15.5 Females - 125 ± 24.1	Group - 167.1 ± 17.2 Males - 167.0 ± 12.9 Females - 167.2 ± 23.3

Analysis of the physiological demands associated with various conditions includes both laboratory and field exercise protocols. These range from progressive maximal oxygen consumption (VO_{2max}) testing to maximal anaerobic power assessment. In addition, some studies have aimed to compare responses between different performance levels of athletes and to analyse the effects of stroke rate, which are summarized in Table 5.

Table 5. Stand Up Paddle Anaerobic Threshold and Energy Expenditure measures.

Authors/Year	Protocol	Findings
Schram et al., 2016a	Laboratory test, progressive VO_{2max} ergometer protocol beginning at 5 Watts (W) with an increase of 5 W every minute until individual burnout. Field test, Progressive VO_{2max} starting at 30 strokes/min and increasing cadence by 5 strokes/min each min, until individual burnout.	Field - VO_{2max} (45.48 ± 6.96 mL · kg ⁻¹ · min ⁻¹). Laboratory - VO_{2max} (43.20 ± 6.67 mL · kg ⁻¹ · min ⁻¹).
Schram et al., 2016b	Laboratory test, the ergometer VO_{2max} protocol began at an initial of 5 W with a 2 W increase each minute until volitional exhaustion. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	Aerobic (+23.57 %) and anaerobic fitness (+41.98 %) improvements.
Schram et al., 2016c	Laboratory test, progressive VO_{2max} ergometer protocol beginning at 5 W with an increase of 5 W every minute until individual burnout. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	Elite - VO_{2max} 43.7, s = 5.89 mL · kg ⁻¹ · min ⁻¹ , anaerobic power outputs 35.7, s = 11.1 W. Recreational - VO_{2max} 31.9, s = 7.68 mL · kg ⁻¹ · min ⁻¹ , anaerobic power outputs 25.0, s = 11.7 W Sedentary - VO_{2max} 20.35, s = 3.69 mL · kg ⁻¹ · min ⁻¹ , anaerobic power outputs 13.5, s = 7.1 W.
Schram et al., 2017b	Laboratory test, the ergometer VO_{2max} protocol began at an initial of 5 W with a 2 W increase each minute until volitional exhaustion. The maximum anaerobic power, paddled maximally for 10 s from a stationary start.	Aerobic fitness improved by 25.0% in the male (+ 5.5 ml/kg/min) and 42.3% in the female (+ 12.2 ml/kg/min).
Castañeda-Babarro et al., 2020b	Incremental exercise test was conducted to assess maximal oxygen uptake and peak power output (PPO). Second test, 3 trials of 8 min each at 75% of PPO reached in the first test session. 3 cadences were carried out in different trials randomly assigned between 45–55 and 65 strokes-min ⁻¹ (spm).	Respiratory exchange ratio (RER) at 4-min than at 8-min in 55 spm (4-min, 0.950 ± 0.065 vs. 8-min, 0.964 ± 0.053) and 65 spm cadences (4-min, 0.951 ± 0.030 vs. 8-min, 0.992 ± 0.047). VO_2 and lactate were lower at 45 spm (VO_2 , 34.4 ± 6.0 mL·kg ⁻¹ ·min ⁻¹ ; Lactate, 3.5 ± 1.0 mmol·l ⁻¹), at 55 spm (VO_2 , 38.6 ± 5.2 mL·kg ⁻¹ ·min ⁻¹ ; lactate, 4.2 ± 1.2 mmol·l ⁻¹

Table 5. Stand Up Paddle Anaerobic Threshold and Energy Expenditure measures (continued).

Authors/Year	Protocol	Findings
Willmott et al., 2020	Laboratory test, $\text{VO}_{2\text{peak}}$ ergometer, outset at 20 strokes min^{-1} and afterwards growing at 3 strokes min^{-1} until individual burnout. Incremental SUP trials - Paddled for 5-min at stroke rates of 10, 20 and 30 strokes min^{-1} ; Field tests - Paddled for 10, 20 and 30 strokes min^{-1} for 5-min per step.	Laboratory: V_{O_2} , EE and METs. 10 spm - 0.68 ± 0.19 (L min^{-1}); 3.3 ± 1.0 (kcal min^{-1}); 2.7 ± 0.5 ; 20 spm - 1.09 ± 0.18 (L min^{-1}); 5.5 ± 0.9 (kcal min^{-1}); 4.4 ± 0.7 ; 30 spm - 1.52 ± 0.31 (L min^{-1}); 7.6 ± 1.6 (kcal min^{-1}); 6.1 ± 1.2 . Field: Estimated (V_{O_2} , EE, METs) 10 spm - 0.72 ± 0.28 (L min^{-1}); 3.6 ± 0.9 (kcal min^{-1}); 2.7 ± 0.9 ; 20 spm - 1.01 ± 0.24 (L min^{-1}); 4.3 ± 1.8 (kcal min^{-1}); 3.5 ± 1.0 ; 30 spm - 1.32 ± 0.36 (L min^{-1}); 6.3 ± 2.1 (kcal min^{-1}); 4.6 ± 1.4 .
Bakilian et al., 2020	Field test, CV determination: 3 best performances at 400, 500 and 800m, adopting distance-time relationship. OBLA determination: 3 efforts at 85, 90, and 100% of maximal 500m effort to determine the velocity related to $3.5 \text{ mmol}\cdot\text{L}^{-1}$ of lactate. $\text{V}_{30\text{min}}$ determination: a 30-minute continuous effort to determine the $\text{V}_{30\text{min}}$.	OBLA ($2.35 \pm 0.13 \text{ m}\cdot\text{s}^{-1}$) and the alternative methods (CV: $2.42 \pm 0.20 \text{ m}\cdot\text{s}^{-1}$ and $\text{V}_{30\text{min}}$: $2.32 \pm 0.13 \text{ m}\cdot\text{s}^{-1}$). The mean $[\text{La}^-]$ after the 30-minute continuous effort was $3.9 \pm 0.2 \text{ mmol}\cdot\text{L}^{-1}$.

Discussion

The main objective of this study is to present and analyse the existing body of research published in the field of SUP, with an emphasis on future research. In particular, the number of publications focusing on the performance dimensions of SUP remains relatively limited compared to the rapid increase in the sport's popularity observed over the past decade. A total of 21 articles were included in this systematic review and divided into four different categories: anthropometry, biomechanics, physiology and equipment, materials, and race behaviour. A comprehensive analysis of these articles is presented in the following sections.

Anthropometry

The studies showed some variability in body fat percentage. For example, in one study Schram et al. (2014), the collective group had an average body fat percentage of 17.5%, with males having a lower average of 13.4% compared to 24.4% for females. Another study by Schram et al., (2016a) showed a reduction in the average body fat percentage for the entire group of 15.87%, again with males having a lower average of 11.13%

compared to 22.98% for females. In addition, elite SUP athletes had a mean body fat percentage of 15.5%, suggesting a leaner body composition compared to the general population Schram et al. (2016c). Additional research Burgess & Bommarito (2019), suggested that preparation for SUP competitions could result in a decrease in body fat, with an average of 19% at baseline and 17% during race week. Overall, participants generally had an average BMI within the range considered normal for adults, ranging from 18.5 to 24.9 kg/m² (Schram et al., 2014, 2016a, c). However, some studies reported different values. For example, experienced SUP practitioners reported an average body fat percentage of 24.3% and a BMI of 24.3 kg/m², with an average height of 170 cm and an average weight of 70.5 kg (Schram et al., 2019). In other cases, data are presented for all groups combined and by gender. Mean body fat percentages ranged from 23.50% to 24.90%, BMIs ranged from 1.67 to 1.79 kg/m², and mean weights spanned from 65.75 kg to 80.66 kg (MacArthur et al., 2021). These observations highlight the diversity inherent in the anthropometry of SUP practitioners, demonstrating a spectrum of physical characteristics within this population. The sedentary population (Schram et al., 2016b, 2017a) also demonstrated diversity in body fat percentage, BMI, height, and weight.

In summary, the research conducted on SUP athletes revealed variations in body fat percentage, BMI, height, and weight. The results suggest that, overall, SUP practitioners have average body fat and BMI levels within the range considered normal for adults. Specifically, gender differences were found, with males having lower average body fat and BMI values compared to females. Elite SUP athletes had a leaner body composition and lower average body fat percentage compared to the general population. In addition, there may be a reduction in body fat prior to SUP competition. However, it is important to note that there was variability in the reported means among the different studies. Body fat percentage, BMI, height, and weight varied within these studies, demonstrating the range of physical characteristics among SUP practitioners. This heterogeneity may be due to factors such as fitness level, experience, gender, age, and individual characteristics. Finally, studies of sedentary individuals also revealed a range of body fat percentage, BMI, height, and weight measurements. In conclusion, the available data underscore the range of anthropometric measures observed among SUP practitioners and serve as a testament to the physical heterogeneity inherent in this population.

Biomechanics

Understanding the biomechanical principles applied to SUP can help identify limiting factors to performance, compare athlete groups, optimize paddling technique, and prevent injury. Despite the limited scope of the studies, their findings may prove invaluable to coaches, therapists, and participants who need to maximize performance and minimize the risk of injury during exercise (Schram et al., 2019). Therefore, topics such as time-motion analysis, stroke parameters, EMG, and global positioning system (GPS) will be addressed. Time-motion analysis (TMA) is a reliable method for analysing athletic performance by examining video footage frame by frame. These systems are designed to track the motion of body segments, derive joint and segment kinematics, and provide additional information through further processing using complex muscle and/or skeletal models (Ortega & Olmedo, 2017). Motion analysis has been widely used in various sports for quantitative purposes, including evaluation of technique and competition (Marqués et al., 2017). The proliferation of high-resolution cameras in mobile communication devices has democratized this form of analysis (Hood et al., 2012), making it a valuable tool for evaluating SUP performance.

The importance of technique in SUP is underscored by the association between less-than-optimal stroke biomechanics and shoulder, elbow, and back injuries observed in similar sports such as kayaking and outrigger paddling (Hagemann et al., 2004; Schram et al., 2019). The first study to investigate the kinematics of the SUP stroke found significant differences in joint kinematics between experienced and inexperienced participants (Schram et al., 2019). Specifically, inexperienced participants demonstrated greater total shoulder range of motion (ROM) (78.9 ± 24.9 vs. 56.6 ± 17.3) and less hip ROM (50.0 ± 18.5 vs. 66.4 ± 11.8) than experienced participants. In addition, experienced participants had more shoulder motion at the end of the paddle stroke (74.9 ± 16.3 vs. 35.2 ± 28.5 minimum shoulder flexion) and more elbow extension (6.0 ± 9.2 minimum elbow flexion vs. 24.8 ± 13.5) than inexperienced participants. These results suggest that experienced paddlers perform a more efficient SUP stroke, possibly due to a larger catch angle and longer stroke length, resulting in a higher peak power output. Differences in ankle-to-hip power and knee angle also suggest that experienced paddlers use more muscle groups during the stroke, resulting in greater overall efficiency. One study Ost et al., (2017) examined the effects of SUP training on balance stability in older adults. Participants performed various demanding postures to assess their balance before and after the training. Kinematic analysis of body sway was performed by attaching flat markers to the acromion of the right shoulder and the seventh cervical vertebra using the KINOVEA software. The

results showed a significant reduction in trunk sway in the SUP training group compared to the control group. This improvement was observed in both the Romberg posture and the tiptoe posture. Furthermore, SUP training also resulted in improved balance stability under conditions of visual deprivation.

In the context of stroke parameters in SUP and the distances achieved, it is important to distinguish between those obtained during training sessions, competitive events, and study protocols. In a competitive context, during a marathon race Schram et al., (2017b), there were differences in the distance covered due to external variables on the race day and their consequent impact on results. The results showed that the average distance covered by the participants was 13.56 km, ranging from 13.34 km to 13.87 km. In the calm water field tests Bakilian et al. (2020) and Neiva et al. (2020), subjects performed 30 minutes of continuous exercise and covered a distance of $4,173.8 \pm 241.8$ m and 3,700 m, respectively. In the laboratory ergometer tests Schram et al. (2016b), the values for the aerobic and anaerobic performance conditions were presented separately for the baseline, pre- and post-training tests. For the aerobic condition, the mean distance covered was 366.68 ± 71.90 m in the baseline test, 336.21 ± 101.97 m in the pre-training test, and 486.80 ± 134.64 m in the post-training test. For the anaerobic condition, the mean distance covered was 14.90 ± 2.96 m in the baseline test, 15.28 ± 2.68 m in the pre-training test, and 17.17 ± 2.48 m in the post-training test. In terms of profiling (Schram et al., 2016c) and providing original data on elite SUP athletes, as well as comparisons with recreational and sedentary individuals with no prior exposure to the sport, men achieved the following distances in aerobic testing: 747.59 ± 128.66 m for the elite group, 503.51 ± 159.97 m for the recreational group, and 368.90 ± 68.42 m for the sedentary group. For the maximum anaerobic power tests, the distances achieved were 20.60 ± 3.08 m for the elite group, 17.29 ± 3.60 m for the recreational group, and 14.07 ± 2.88 m for the sedentary group. The studies reviewed represent a wide range of distances covered in different contexts. In competitive events, participants covered an average distance of 13.56 km. In field tests, one athlete achieved a total distance of 3700 m in 30 minutes in calm water, while in another study, subjects achieved a total distance of $4,173.8 \pm 241.8$ m in 30 minutes of continuous exercise. In laboratory ergometer tests, the distances covered were presented separately for different conditions, such as aerobic and anaerobic, and ranged from 14.90 m to 486.80 m. In a study comparing elite athletes, recreational athletes, and sedentary individuals, the distances covered also showed differences between the groups (Schram et al., 2016c).

When analysing speed, the marathon performance showed a mean speed of 9.78 ± 0.70 m/s, with male participants showing a slightly higher mean speed of 10.13 ± 0.53 m/s compared to female participants, who maintained a mean speed of 9.07 ± 0.41 m/s (Schram et al., 2017a). During maximal aerobic SUP testing, speeds were slightly slower. Under calm water conditions without current interference, an athlete achieved a mean speed of 2.19 ± 0.32 m/s during a maximal SUP test (Neiva et al., 2020). Using an ergometer Schram et al., 2016c, the maximal speed during an aerobic test was 2.18 ± 0.16 m/s for the elite class, 1.93 ± 0.24 m/s for the recreational group, and 1.50 ± 0.15 m/s for the sedentary group. When assessing anaerobic performance, the elite group reached a maximum speed of 2.35 ± 0.32 m/s, the recreational group reached 1.99 ± 0.40 m/s, and the sedentary group reached 1.62 ± 0.31 m/s. Notably, both tests showed significant differences between the elite group and the other participant groups.

Furthermore, the literature has shown that the maximum speed values were significantly increased in the field environment (average of 3.09 ± 0.32 m/s) compared to the laboratory setting (2.17 ± 0.13 m/s) (Schram et al., 2016a). However, the differences in speed measurements between the two settings are likely due to the different methods used to quantify speed. The laboratory-based speed measurement is based on the moment of inertia of the ergometer flywheel, whereas the field-based measurement was obtained using the integrated GPS and gas analysis system. In summary, some studies (Schram et al. 2016a, b, c 2017b and Neiva et al. 2020) reported different values for maximal speed in different conditions and participant groups. A higher mean maximal speed was found in the field compared to the laboratory setting. In addition, elite athletes had higher maximal speeds in both aerobic and anaerobic conditions compared to recreational and sedentary individuals. Furthermore, gender differences in maximal speeds were observed, with male participants achieving higher mean and maximal speeds than female participants.

During a 30-minute session in calm waters, the record paddle rate was 52.63 ± 2.62 paddles per minute, with an average distance covered per paddle of 2.39 ± 0.39 meters (Neiva et al., 2020). The use of ergometers to assess the maximum paddle rate (the maximum number of SUP paddles per minute) and the average length of each SUP paddle varied significantly between different groups (Schram et al., 2016c). The elite group had a maximum paddle rate of 69.6 paddle/min and a mean paddle length of 2.19 meters, while the recreational group had a maximum paddle rate of 55.47 paddle/min and a mean paddle length of 2.24 meters. In contrast, the sedentary group had a maximum paddle rate of 42.27 paddle/min and a mean paddle length of 2.34 meters. These results suggest that elite paddlers, on average, performed more paddles

in each time period but paddled for a shorter average paddle length compared to their recreational and sedentary counterparts. In one study Schram et al., (2016b), the results showed a significant increase in mean paddle length (2.38 ± 0.46 m at baseline and 2.52 ± 0.40 m after training) and maximum paddle length (2.89 ± 0.66 m at baseline and 2.96 ± 0.61 m after training) after SUP training. These changes indicate an improvement in paddling efficiency and power. In addition, the maximum paddle rate (paddles/min) also increased after training (43.77 ± 4.71) compared to baseline (41.15 ± 9.10), suggesting an improvement in the ability to perform high-speed paddles. During a 30-minute session, an individual participant maintained an average paddle rate of approximately 52.63 paddles per minute, with each paddle covering an average of 2.39 meters (Neiva et al., 2020). Significant differences in paddle rate and paddle length were found between the different groups, with the elite group performing higher rates with shorter lengths compared to the recreational and sedentary groups (Schram et al., 2016c). In contrast, one study Schram et al. (2016b) reported a significant improvement in mean and maximal paddle length, suggesting an improvement in paddle efficiency and power after SUP training, and an increase in maximal paddle rate, suggesting an improvement in the ability to perform high-speed paddles.

Surface electromyography (sEMG) is a widely used research tool in sports due to its ability to provide dynamic analysis, making it an important tool for optimizing movement, sports equipment, training techniques, and, ultimately, sports performance (Farina, 2006; Vigotsky et al., 2018). The comprehensive assessment and feedback provided by sEMG analysis of muscular action allows for the optimization of athletic training and performance (Clarys & Cabri, 1993). In addition, a complete understanding of the biomechanical demands of the sport can be achieved by synchronizing the EMG system with other technologies, such as cameras and electrogoniometers, that provide kinetic and kinematic data (Türker & Sze, 2013). This integration allows researchers to gain a more accurate and detailed understanding of the movement patterns and muscular activity and to use this information to improve training and performance. EMG analysis can provide valuable information about muscle activation patterns and timing during different phases of the paddle stroke in the context of SUP (Ruess et al., 2013). Tsai et al., (2020) aimed to compare muscle activation patterns in kneeling and standing SUP positions using EMG analysis. The researchers measured the activity of the rectus femoris, biceps femoris, tibialis anterior, gastrocnemius, erector spinae, and upper trapezius muscles while participants paddled in both positions. The results showed significantly higher activation of the rectus femoris and biceps femoris muscles in the standing position compared to the kneeling position, while the anterior tibialis muscle showed significantly higher activation in the

kneeling position compared to the standing position. The gastrocnemius muscle showed similar activation levels in both positions. The erector spinae and upper trapezius muscles also showed higher activation levels in the standing position, although the difference was not statistically significant. Overall, the study suggests that the standing position in SUP results in greater activation of the leg muscles, while the kneeling position results in greater activation of the anterior tibialis muscle.

The use of GPS in sports allows practitioners to evaluate athletic training programs and researchers to better investigate applied research questions (Malone et al., 2017). Such devices have primarily been used to study exercise monitoring in athletes (Cummins et al., 2013) and neuromuscular fatigue (Buchheit et al., 2015). To date, there are only seven studies that have used GPS technology in SUP to track athletes' events (Schram et al., 2017a), sessions (MacArthur et al., 2021, Suari et al., 2018), and laboratory or field studies (Schram et al., 2016a; Willmott et al., 2020; Castañeda-Babarro et al., 2020a; Neiva et al., 2020). These studies have provided valuable information on the external demands of SUP in competition, session, or testing, such as stroke rate, distance per stroke, distance paddled by athletes, speeds generated while surfing, course completion time, course distance, average speed, maximum speed, peak speed, distance per minute, and the impact of weather conditions. These variables provide insight into the sport and the workloads encountered, providing coaches with valuable information that can be used to develop and prescribe training/session programs.

Physiology

Physical performance in various competitive sports events is largely dependent on the integrated state of various physiological mechanisms (Ghost, 2004). Thus aerobic, and anaerobic capacities are key determinants of elite profiles (Schram et al., 2016a) and performance outcomes (Schram et al., 2017a). Monitoring HR, anaerobic threshold, and energy expenditure during SUP are the indicators discussed below. HR has been analysed in cross-sectional observational studies (Schram et al., 2016c; Willmott et al., 2020; McArthur et al., 2021) in the (Castañeda-Babarro et al., 2020b), in the field (Schram et al., 2016a; Neiva et al., 2020), in training programs (Schram et al., 2016b), in competitions (Schram et al., 2017b), and in training sessions (Suari et al., 2018). A total of eight studies were conducted with SUP practitioners of different performance levels. The reviewed studies suggest that HR is an important physiological response during SUP and can be used to monitor exercise intensity and performance. Some studies Schram et al., 2016a, b, c and 2017a, indicate that there were no significant

differences in maximal HR between elite, recreational, and sedentary participants and that HR measurements were consistent between laboratory and field testing. In addition, HR remained relatively stable after the implementation of a training program, suggesting that it is a reliable indicator of exercise intensity. SUP surfers spend a significant portion of their sessions at HRs above 70% of their maximum HR (Suari et al., 2018). The highest HRs have been observed when surfers fall off the board and when paddling back out, suggesting that these activities are particularly demanding. Paddling cadence can affect HR, with higher cadences resulting in higher HRs during an 8-minute test (Castañeda-Babarro et al., 2020b). Laboratory data suggest that as the SUP stroke rate increases, HR also increases, reflecting an increase in exercise intensity. Field data suggest that as the SUP stroke rate increases in the outdoor environment, the HR also increases, reflecting a higher exercise intensity Willmott et al. (2020). Comparing the two situations, the mean HR and percentage of maximal HR were higher during the laboratory test at 30 strokes per minute but not at 10 or 20 strokes per minute. During a 30-minute maximal effort SUP test, HR remained relatively stable, indicating that athletes were able to maintain a consistent level of intensity throughout the test Neiva et al. (2020). Male and female participants have similar peak HRs during SUP, but males have a higher average HR McArthur et al., 2021. In addition, SUP can be considered a vigorous aerobic activity based on HRs relative to the predicted maximum HR for age.

Overall, the reviewed studies suggest that HR is a valuable indicator of exercise intensity and performance during SUP, with HRs above 70% of maximum HR being common during sessions. Paddling cadence can also affect HR, with higher cadences resulting in higher HRs. It is important to control the pace during SUP to maintain an appropriate level of intensity throughout the session. A total of seven studies have evaluated the anaerobic threshold and energy expenditure during SUP. These assessments were performed both in the laboratory using ergometers (Schram et al., 2016a, b, c; Schram et al., 2017b; Castañeda-Babarro et al., 2020b), by comparing data from laboratory and field conditions (Schram et al., 2016a; Willmott et al., 2020), and by field testing Bakilian et al. (2020). Peak aerobic power was significantly higher in elite SUP athletes compared to the recreational and sedentary groups (Schram et al., 2016c). Peak aerobic power was also significantly higher in the elite group than in the others. The study also found gender differences, with elite men having higher VO_{2max} than elite women, and sedentary women having the lowest mean VO_{2max} . Field-based measures of maximal aerobic power were significantly higher (+5.28%) than laboratory-based measures (Schram et al., 2016a). Men had significantly higher maximum aerobic power than women in both the laboratory and the field, and there

was a strong positive correlation ($r = 0.907$) between absolute VO_{2max} recorded in the laboratory and the field. Field measurements were higher in 80% of the subjects tested, with only two subjects showing higher values in the laboratory. Six weeks of SUP training resulted in significant improvements in both absolute and relative aerobic power, with increases of 18.86% and 23.57%, respectively (Schram et al., 2016a). In addition, there was a weak negative correlation ($r = -0.32$) between the age of participants and the percentage increase in VO_{2max} throughout the study. The study also found significant improvements in anaerobic fitness, with a 41.74% increase in anaerobic power production and a 42.11% increase in relative power production over the training period. A long-term intervention (Schram et al., 2017b) showed significant improvements in both aerobic (2.8 ml/kg/min; +13.0%) and anaerobic (2 W; +20.8%) power. The most significant improvements were observed in one participant who increased aerobic power by 6.3 ml/kg/min and anaerobic power by 5.3 W.

In the laboratory, significant main effects were observed for energy expenditure (EE), metabolic equivalents (METs), VO_2 , and ventilation (VE) as SUP paddling rates progressed from 10 to 30 strokes per minute. Similarly, in the field setting, significant main effects were observed for estimated EE, METs, and VO_2 , with all variables increasing significantly as SUP paddling rates increased from 10 to 30 strokes per minute. Moreover, economy (45.3 ± 5.7 KJ·l⁻¹ at 45 rpm vs. 38.1 ± 5.3 KJ·l⁻¹ at 65 rpm; $p = 0.010$) and gross efficiency ($13.4 \pm 2.3\%$ at 45 rpm vs. $11.0 \pm 1.6\%$ at 65 rpm; $p = 0.012$) were higher at 45 rpm than at 65 rpm during an 8-minute test. The respiratory exchange ratio was lower at 4 minutes than at 8 minutes at both cadences of 55 rpm (4 min, 0.950 ± 0.065 vs. 8 min, 0.964 ± 0.053) and 65 rpm (4 min, 0.951 ± 0.030 vs. 8 min, 0.992 ± 0.047 ; $p < 0.05$). In addition, VO_2 and lactate were lower at 45 rpm (VO_2 , 34.4 ± 6.0 mL·kg⁻¹·min⁻¹; lactate, 3.5 ± 1.0 mmol·l⁻¹) compared to 55 rpm (VO_2 , 38.6 ± 5.2 mL·kg⁻¹·min⁻¹; lactate, 4.2 ± 1.2 mmol·l⁻¹) and 65 rpm (VO_2 , 38.7 ± 5.9 mL·kg⁻¹·min⁻¹; lactate, 5.3 ± 1.8 mmol·l⁻¹) at 8 minutes. Additionally, lactate was higher at 65 rpm than at 55 rpm at 8 minutes. Athletes had a higher aerobic and anaerobic capacity compared to recreational and sedentary individuals. There were also gender differences, with elite males having higher mean VO_{2max} values than elite females and sedentary females having the lowest VO_{2max} values. In addition, maximal aerobic power measured in the field was found to be significantly higher than that measured in the laboratory. Studies have also shown that SUP rowing rates affect several physiological measures, with all variables increasing significantly as SUP rowing rates increased from 10 to 30 strokes per minute. Finally, economy, and gross efficiency were

found to be higher at lower rowing rates (45 strokes per minute) than at higher rates (65 strokes per minute) during an 8-minute test.

SUP Equipment's, materials, and race behaviour

Equipment innovation aims to increase access to sport and improve performance (Romanin et al., 2021), and it is necessary to understand the variables that affect performance before designing equipment. Once these variables are identified, equipment can be designed to modify them and achieve the desired outcomes (Stefanyshyn & Wannop 2015). The ergometer is an important piece of equipment for a rower because it facilitates the in-water rowing mechanism (Harun et al., 2020). There are notable differences between in-water strokes and out-of-water strokes when using an ergometer or rowing boat, particularly with respect to the gear ratio, the pattern of force increase, and the magnitude of the force produced (Lamb, 1989; Kleshnev, 2005). In SUP, the devices that have been used for biomechanical and physiological analysis include swimming ergometers (Castañeda-Babarro et al., 2020b) and SUP-specific ergometers (Schram et al., 2016a, b, c; 2017b; 2019; Willmott et al., 2020).

In technology assessment, one study evaluated the intra-test reliability of a proposed outdoor field evaluation methodology for three levels of SUP technology Dyer (2018): boards, paddles, and fins. The study compared two different SUP boards: the high-tech Sprint board and the basic Allstar board. The sprint board outperformed the Allstar board in terms of paddle speed and stability, while the Allstar board had the worst performance. The study also evaluated three types of SUP paddles: carbon, hybrid, and aluminium. The results showed that the high-tech carbon paddle performed better in terms of paddle speed. However, there were no significant differences in performance regarding board stability or wind resistance. Finally, three types of SUP fins were evaluated: carbon, fiberglass, and plastic fins. The high-tech carbon fins performed better in terms of paddle speed and stability, while the basic plastic fins performed the worst. Another study proposes a parametric method for customizing fins through additive manufacturing (3D printing) (Novak, 2021). The methodology is based on a parametric model that allows users to adjust the dimensions of the fins according to their preferences and abilities. Specifically, the fin system, its position on the board, can't, depth, sweep, base length, base foil profile, tip sharpness, tip thickness, and overall dimensions can be adjusted within a limited range of values, resulting in a 3D printable geometry. The method of creating the parametric system is sufficiently detailed to be replicable and constructed by designers, and future research directions

are outlined to improve SUP performance and expand the well-established culture of experimentation within the sport.

In evaluating the stability of the human-SUP system under varying water conditions, one study Chen et al., (2018) found that the position of the rider on the board plays a critical role in the stability of the system, with a central position providing greater stability. In addition, the study developed a stability map for the coupled system by modelling the governing equations of the buoyant body system and performing asymptotic stability analysis. The analytical results of the eigenvalue contours from the stability analysis were compared to current industrial SUP dimensions, allowing users to select a SUP board that balances stability and manoeuvrability.

An analysis of two SUP events from different years to determine if there were any changes in their participation or behaviour during the race and whether such events should be approached differently by practitioners, Dyer (2021) suggested that the differences were more related to the distance of the race than to the specific characteristics of each event. The study also suggested the use of a Perceived Intensity Chart diagram to assess the competitiveness and quality of a SUP event. In addition, optimizing equipment choices and implementing technologies such as GPS trackers can positively impact competitors' performance and provide a better understanding of the dynamics of SUP racing.

Overall, the studies highlighted the importance of equipment innovation in improving performance and increasing accessibility to the sport of SUP. The use of ergometers and specific biomechanical and physiological analysis devices can help to understand the variables that affect performance and facilitate the design of equipment to modify them. Furthermore, technological evaluations of SUP equipment, such as boards, paddles, and fins, have shown significant differences in performance based on material and design. Finally, understanding the stability of the human-SUP system in varying water conditions is critical to selecting an SUP board that balances stability and manoeuvrability. In conclusion, these studies demonstrate the potential for technology and innovation to enhance the sport of SUP and encourage research to improve performance and expand the culture of experimentation within the sport.

Limitations of the Study

The first article that met the inclusion criteria for this study was published in 2014, coinciding with the resurgence of the field at the beginning of the century. A lack of both overall studies and comparable studies limited this review. As mentioned

previously, research on SUP performance is an emerging area, and as a result, only 21 studies from a small number of research groups met the inclusion criteria for this review. In addition, the review was limited to English-language publications and conference abstracts, which may have excluded important published studies on SUP performance. Although an extensive database search was conducted, the use of other databases could have further strengthened this review. The studies included in this review were diverse and segmented, lacking consistency in thoroughly characterizing specific domains. Moreover, the diversity of research questions and methodologies used in these studies makes it difficult to compare results and draw concrete conclusions to guide future recommendations. Nevertheless, the volume of SUP-related research is increasing. This trend illustrates the evolution of scientific curiosity in the field of SUP as researchers seek to address pertinent questions that span both broad and specific topics.

Future Research

Future SUP research has significant potential to advance understanding in several research areas. In SUP biomechanics, motion analysis, aided by increasingly accessible motion capture technologies, will facilitate the study of how variables such as paddle angle, stroke length, and rhythm affect performance. The integration of surface electromyography into the study of muscular activation patterns during different phases of the paddle stroke contributes to the understanding of paddle biomechanics. The interplay between physiological factors and SUP performance requires a continued focus on investigating the aerobic and anaerobic capacities of practitioners at different skill levels. Additionally, monitoring HR, anaerobic threshold, and energy expenditure during SUP provides insight into how these physiological factors relate to performance. A more complete understanding of how the physical and technical aspects interact can be achieved by correlating biomechanical, sEMG, and GPS data. Continued improvements in board and paddle materials and design may result in improved performance for practitioners. Ergonomics and technical evaluation of equipment play an equally important role, providing insight into force generation during paddling and the reliability of different types of equipment. From a safety perspective, research into preventative measures and understanding ocean conditions is essential. As SUP grows in popularity, research must also address its environmental impact, with a particular focus on coastal erosion and mitigation methods.

Conclusion

Overall, this review provides a comprehensive and extensive consolidation of current knowledge in areas such as anthropometry, biomechanics, and physiology related to SUP performance, shedding light on key parameters and their implications for practitioners and the sport itself while also highlighting emerging trends. This analysis includes several studies on SUP performance, including differences in performance between different groups of athletes, paddling techniques, exercise intensity, and equipment used. The studies reviewed suggest that SUP athletes have higher levels of muscle mass and lower levels of body fat and use a more efficient SUP stroke, resulting in greater overall efficiency. In addition, the evaluation of SUP equipment technology, such as boards, paddles, and fins, has shown significant differences in performance based on material and design. In SUP, it is important to control the pace in order to maintain an appropriate level of intensity throughout the race. The use of ergometers and specific biomechanical and physiological analysis devices can help to understand the variables that affect performance and facilitate the design of equipment to modify them. Ultimately, these studies demonstrate the potential for technology and innovation to improve the sport of SUP. The importance of the stability of the human SUP system in different water conditions and the need for further research to improve performance and expand the culture of experimentation within the sport should be emphasized.

Chapter 3. Experimental Studies

Study 2. Neuromuscular Assessment of a Stand-Up Paddle Stroke

Abstract

This study analyzed muscle activity during the stand-up paddle stroke, considering the paddling side and the adjacent and opposing muscles relative to the position of the arms during paddling. Methods: Fourteen male paddleboarders performed three trials covering 195 m in which surface electromyography of the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis* were recorded (four-cycle strokes on each side). The data were processed according to percentage of maximum voluntary contraction (% MVC). The MVC activation values (μV) for each muscle were then calculated and presented as percentage MVC (% MVC). Results: The recovery phase accounted for 60% of the paddle cycle, while the pull phase represented 39%. During right-side paddling, higher % MVC was found in the opposite-side *upper trapezius* (24.35%, $p < 0.01$) during the pulling phase and in the adjacent *biceps brachii* (8.36%, $p < 0.03$) during the recovery phase. In left-side paddling, greater % MVC was found in the opposite side *upper trapezius* (27.60%, $p < 0.01$) during the pulling phase and in the opposite-side *triceps brachii* (42.25%, $p < 0.04$) during the recovery phase. Furthermore, the pulling phase exhibited higher MVC in the opposite-side *upper trapezius* compared to the recovery phase, both in the rightside (24.35%, $p < 0.03$) and left-side (27.60%, $p < 0.01$) paddling. Conclusions: these findings help establish the muscular activity of both sides of the paddling technique and the differences between the upper and lower limbs.

Keywords: SUP, paddle sports, muscular activation, EMG, stroke phases.

Introduction

Stand-up paddle boarding (SUP) is a sport that combines elements of surfing and canoeing, allowing paddlers to practice distance paddling and/or surf waves (Walker et al., 2010). It has become a popular and accessible activity with numerous benefits, including improvements in body mass index, aerobic and anaerobic fitness, and multidirectional trunk strength, as well as applications for rehabilitation and fall prevention (Schram et al., 2015; 2016a; 2017a; Castañeda-Babarro et al., 2022; Ruess et al., 2013a). Despite its growing popularity, research on SUP remains limited, with few studies investigating its physiology (e.g., Schram et al., 2016b; Neiva et al., 2020), biomechanics (e.g., Tsai et al., 2020; Hibbert et al., 2023), epidemiology (e.g., Furness et al., 2017; Castañeda-Babarro et al., 2021), and psychology (e.g., Schram et al., 2016b) in both recreational and competitive participants (e.g., Schram et al., 2017b, 2019; Balikian et al., 2020).

The biomechanics of SUP paddling is like dragon boat racing with an entry, drive, and exit phase (Ho et al., 2009). A comparison of paddle stroke mechanics between experienced and inexperienced SUP participants by Schram et al. (2019) revealed that inexperienced participants showed higher overall shoulder action and less hip range of motion than experienced participants. Muscle activation during paddling appears to primarily involve the upper extremities, trunk, hip stabilizers, and knees (Ruess et al., 2013b; Tsai et al., 2020). During SUP in an ergometer and at sea, it was demonstrated that muscle activation during the water-based test started sooner and was maintained longer than that during the ergometer test (Ruess et al., 2013b). Tsai et al., (2020) evaluating different postures, found higher *biceps brachii* activity when paddling on the knees on the board and higher activation of the *external oblique* and *triceps brachii* in the standing position.

Analyzing the muscles involved in paddling, the *upper trapezius* is responsible for producing clavicle elevation and retraction relative to the thorax due to its attachment to the distal clavicle (Hermens et al., 2000). The *biceps brachii* muscle was found to be primarily activated during the recovery phase and the late pull phase. Its role in this context involves assisting in shoulder flexion, aiding the upper hand (the hand opposite to the one holding the paddle) in lifting the paddle and preparing for the subsequent pull phase (Tsai et al., 2020). In the case of the *triceps brachii*, it was observed to mainly engage from the later stage of the recovery phase to the middle stage of the pull phase (Tsai et al., 2020). The *tibialis anterior* muscle was noted for its activation in

maintaining board balance (Fey et al., 2007). Finally, the *gastrocnemius medialis* muscle was found to be activated during the pull phase, with significantly higher activation levels associated with the task of maintaining balance. This heightened activation can be attributed to the higher center of gravity in the standing position and the increased sway movements, which demanded additional effort to ensure stability (Tsai et al., 2020).

During SUP, paddlers can alternate between left- and right-hand sides for paddling (Schram et al., 2016a), involving pushing cycles, controlling the fluid movement of the board and the relative movements of the paddle and the water, consequently, the paddler must continuously change his or her basic attitude to adjust trajectory and balance (Limonta et al., 2010). Therefore, it is important to consider different settings such as the sea and lakes (Willmott et al., 2020). Thus, during recreational SUP practice, participants often alternate paddling sides based on physical or natural conditions. To date, the understanding of paddling on both sides remains limited. Regardless of SUP being described as a full-body activity, understanding the differences between sides is particularly necessary in groups that comprise most participants in this sport. This study aimed to analyze muscle activity during the stroke cycle, considering the paddling side (left and right), comparing the opposite and adjacent muscles to the paddle stroke, and examining activation in the upper and lower limbs, to better understand muscle activation patterns during paddling.

Materials and Methods

Sample and Ethical Procedures

Fourteen SUP recreational right-handed male participants (24 ± 7.1 years, 1.73 ± 1.22 m, 58 ± 15.5 kg, wingspan 1.79 ± 0.87 m, and body mass index 24.2 ± 4.9 kg/m²; mean \pm SD) volunteered to participate in this study after being instructed on the procedures. Participants were only included if they met age requirements (>18 years), had at least 6 months of SUP experience with regular weekly practice (1 to 2 times per week), and were excluded if they had any health risks or conditions that affected paddling performance. Prior to testing, the participants were informed about the benefits and risks of the investigation and signed an institutionally approved informed consent document. This study was approved by the University Ethics Committee (CE-UBI-Pj-2022-042) and all the procedures were in accordance with the Declaration of Helsinki regarding human research.

Procedures

Measurements

Muscle activity was assessed on both sides of the body by surface electromyography (EMG) on a wireless EMG system with built-in accelerometers (Miniwave, Cometa, Milano, Italy; EMGandMotionsTools software 8.7.6.0) and probes equipped with a 7-g Appl. Sci. 2023, 13, 13265 3 of 12 memory and a sampling rate of 2000 Hz at 16 bits. For each subject, the skin under the electrodes was shaved, rubbed with sandpaper, and cleaned with alcohol so that the interelectrode resistance did not exceed 5 KOhm (Afsharipour et al., 2019). Transparent bandages with labels (Hydrofilm®, 10 cm × 12.5 cm, USA) were used to protect the electrodes to isolate them from water (Conceição et al., 2014). Additionally, participants wore custom-made long-sleeved surf suits (Decathlon, Olaian 3/2 mm, Villeneuve-d'Ascq, France) to protect the electrodes and sensors during the trials. The EMG sensors were placed according to the SENIAM recommendations (Kendall™, ECG electrodes, 57 width mm × 34 length mm, gel area 201 mm², sensor area 80 mm², Dublin, Ohio, USA) and the inter-electrode distance between each pair was 20 mm (Dyson et al., 1996). The muscles under analysis in this study were the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis* according to the importance of these muscles in paddling (Tsai et al., 2020).

Maximal Voluntary Contraction

The maximum voluntary contraction (MVC) test is one of the most used methods of the EMG signal normalization (Castelein et al., 2015). Prior to the paddle assessment, to determine the MVC, each subject performed three maximal voluntary isometric contractions on dry land for each muscle analyzed, held for 5 s with a minimum rest interval of 30 s between repetitions. A minimum 1-min rest period preceded each new test position. The MVC procedures were conducted with the application of manual resistance by the examiner, according to positioning guidelines based on the guidelines of both Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) and Noraxon (Scottsdale, AZ, USA.) company (Dyson et al., 1996; Al-Qaisi & Aghazadeh, 2015). To ensure isometric conditions, the examiner made every effort to adjust the counterforce appropriately. For the *upper trapezius* muscle assessment, participants were positioned in a standing posture, and the examiner applied a downward force to their shoulders (Konrad, 2006). Regarding the MVC for the *biceps*

brachii and *triceps brachii*, these assessments were carried out with the elbow flexed at approximately 90 degrees, as described in previous studies (Liu et al., 2013, Roman-Liu et al., 2017). The examiner provided upper arm stabilization to enhance and standardize activation conditions. For the *biceps brachii*, the forearm was in a supinated position, while a neutral forearm position was maintained for the *triceps brachii*. For the *tibialis anterior*, the foot was held in dorsiflexion, and the toes were not extended, maintaining a neutral position of the foot. For the *gastrocnemius medialis*, the foot was placed in plantar flexion with an emphasis on elevating the heel more than pushing the forefoot downward. To achieve maximum pressure in this position, pressure was applied against both the forefoot and the calcaneus, ensuring a pointed, plantar-flexed position of the foot. The maximum value of the resulting EMG envelope was determined, and this was averaged across the trials for each test (Boettcher et al., 2008).

Stand-Up Paddle Stroke Assessment

All conditions were performed with the same SUP board (Itiwit 10'32"5"), paddle (Itiwit 170–220 cm) and in the same location, and before starting, the height of the paddle was individually adjusted (range 1.7–2.2 m) (Willmott et al., 2019). The protocol was performed on an inland lake without current interference where the participants had to paddle in a straight line (Figure 1). Before initiating data collection with the subjects, the temperature and wind were analyzed to assess whether it was possible to perform the trials without interference from external conditions. All trials were carried out in the direction of the wind, being recorded daily, obtaining an average of 3.4 m.s⁻¹ (gentle breeze) using the Beaufort Wind Scale (National Weather Service).

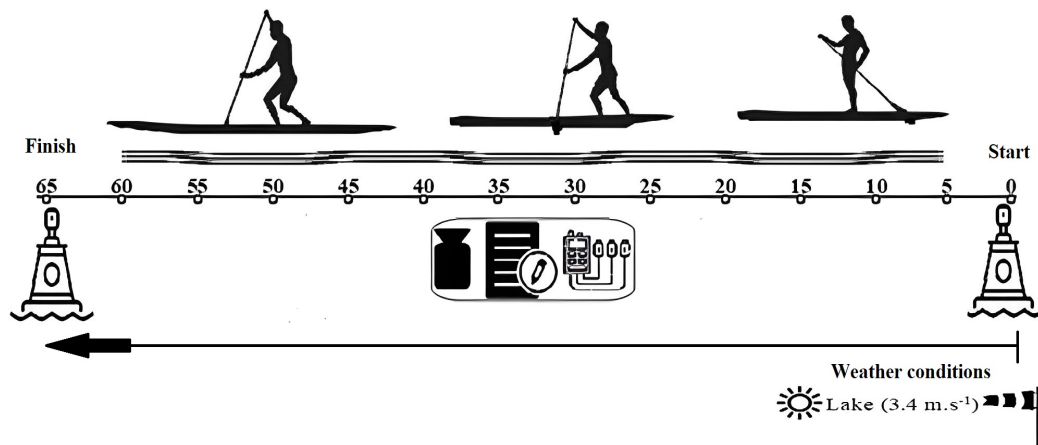


Figure 1. Schematic overview of the SUP field protocol.

Before initiating the official trials, the participants performed a 5-min warm-up where they self-selected stroke frequency. Each subject performed 3 trials of stand-up paddling on the water at an individual pace. Then, to maintain the forward movement when paddling, the participants were instructed to alternate paddle sides after three strokes (Tsai et al., 2020), during three trials of 65 m, the total distance covered was 195 m in a straight line limited by two floats indicating the beginning and end of the course. The EMG measurement was synchronized with a digital video camera (Panasonic, DC-FZ 1000II, Osaka, Japan) fixed on a tripod (Falcon eyes, FT-120, Hoogeveen, The Netherlands) positioned at a distance of 20 m, perpendicular to the course, to record the entire procedure. To synchronize the data, the subjects had to stand on the board in a T position for 5 s and then tap on their arm *biceps brachii* three times before starting the trials. The same gesture of tapping the *biceps brachii* three times occurred when each subject finished the course.

Data Analysis

Initially, each video was cut according to the trials (Windows, media player) to later synchronize the data with the EMG software (EMG and Motion Tools, V8, Cometa, Bareggio Mi, Italy). The video analysis was connected with the event. In this study, synchronization was processed by identifying visible peaks in the accelerometer signal. In this way, it was possible to find the final and initial time of a propulsive phase in the

EMG data through the video sequence, with an accuracy of 33.3 ms on a video frame. The “pulling” phase is the process in which the blade is completely immersed in water and is swung backward to generate forward power (Michael et al., 2009). In the “exit” and “recovery” phases, the blade is pulled out of the water and returned to the starting position before starting the next catch phase (Tsai et al., 2020). Event times were checked by a second observer to identify errors. After that, four left and right cycle strokes were analyzed. The first six cycle strokes of both sides were excluded from the analysis, as well as the first stroke of each cycle, to eliminate the paddle transferring from side to side, which influences the cycle parameters. After, phase cycle parameters (s) and stroke time parameters (%) were calculated. Signal processing was started by applying filters to the MVC file. EMG sensors received raw EMG data and the first frequencies were removed with the following filters: (i) a low pass filter with a cutoff frequency of 400 Hz and Butterworth filter with an order of 4; (ii) a high Pass filter with a cutoff frequency of 20 Hz and Butterworth filter with an order of 4. The maximum MVC activation values (μV) for each muscle were then calculated and presented as percentage MVC (% MVC). The last procedure was to apply the same filters to the signal taken from each trial, as well as to apply the MVC to the trial file. Finally, the mean cycles were exported to an Excel file.

Statistical Analysis

Descriptive statistics were calculated including mean, standard deviation, and coefficient of variation for each phase and side. The normality plot tests of Shapiro–Wilk were applied and, therefore, the Student’s t-test was used to compare the two sides, the right and left sides, relative to the paddling movement. The statistical significance was set to $p \leq 0.05$. The Cohen’s D effect size was calculated as an indicator of the magnitude of the effect, with D considered a small effect if 0.8 (Lakens, 2013). Statistical analysis was carried out using SPSS statistical software (IBM Corp., Armonk, NY, USA, version 20.0).

Results

Regarding the time in stroke cycle, the participants spend approximately 60% in the recovery phase and 39% in the pull phase. There were no significant differences in the stroke cycle parameters between left and right paddle stroke cycles (Table 1).

Table 1. Stroke cycle parameters regarding time (seconds) and percentage (%) of stroke phases (recovery and pull phases) expressed as mean (mean \pm SD). *p*-values and effect sizes are also shown.

	Paddle Side	Mean \pm SD	<i>p</i> -value	Cohen's D	95% CI for Cohen's D	
					Lower	Lower
Stroke Time (s)	Left	1.50 \pm 0.25	0.93	-0.03	-0.77	0.71
	Right	1.51 \pm 0.27				
Recovery Time (s)	Left	0.92 \pm 0.20	0.83	0.08	-0.66	0.82
	Right	0.91 \pm 0.19				
Pull Time (s)	Left	0.60 \pm 0.11	0.85	0.07	-0.67	0.82
	Right	0.59 \pm 0.12				
Recovery Phase (%)	Left	60.04 \pm 5.62	0.66	-0.16	-0.91	0.57
	Right	60.97 \pm 5.56				
Pull Phase (%)	Left	39.96 \pm 5.62	0.66	0.16	-0.57	0.91
	Right	39.03 \pm 5.56				

We observed higher muscle activation during the recovery phase for the upper limbs on the left paddling side in the *biceps brachii* adjacent (18.6% MVC), *upper trapezius* adjacent (18.3% MVC) and opposite (33.1% MVC). During the pull phase, higher activation was observed in the *triceps brachii* adjacent (38% MVC) and opposite (51% MVC) (Figure 2). Regarding the lower limbs, higher muscle activation was observed in the *tibialis anterior* for the adjacent and opposite sides of the body, but higher activation in the pull phase compared with the recovery phase (Figure 2).

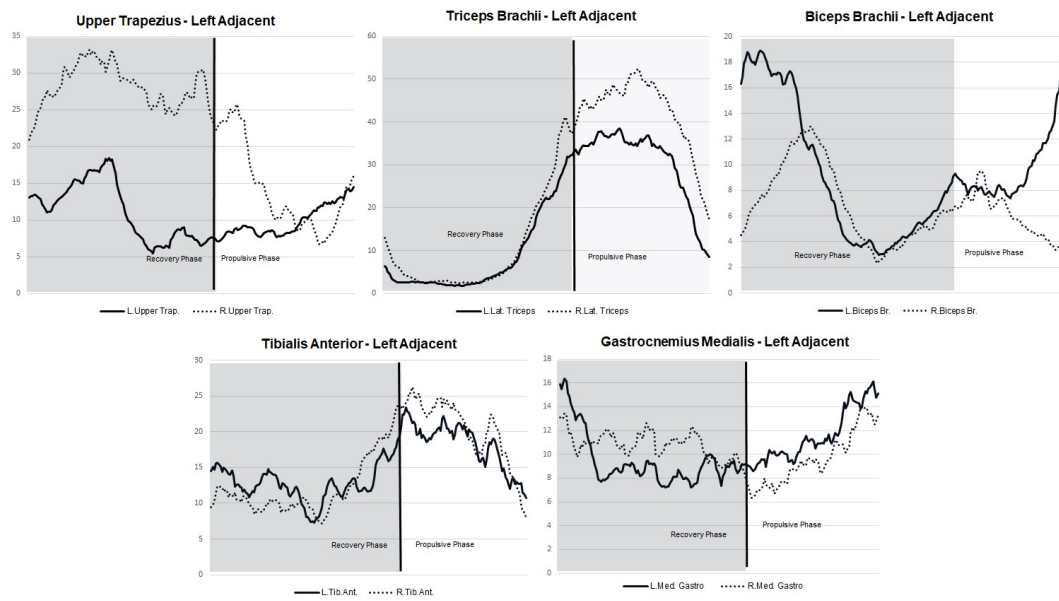


Figure 2. Muscle activity (%MVC) patterns for the left paddling side stroke concerning the stroke cycle and regarding the muscles of the opposite and adjacent sides of the body.

For the upper limbs on the right paddling side, higher muscle activation was observed during the recovery phase in the muscles: *upper trapezius* adjacent (27.4% MVC) and opposite (20.4% MVC). During the pull phase, higher activation was observed in the *triceps brachii* adjacent (39.1% MVC) and opposite (39.49% MVC). The lower limbs had the same behavior for muscle activity as the left paddling side (Figure 3).

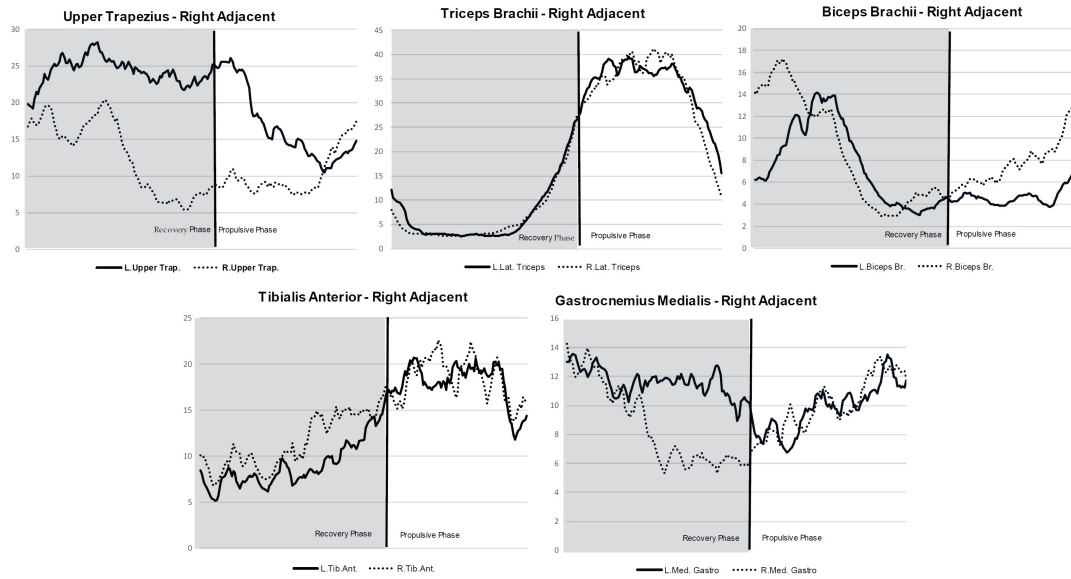


Figure 3. Muscle activity (%MVC) patterns for the right paddling side stroke concerning the stroke cycle and regarding the muscles of the opposite and adjacent sides of the body.

On the right paddling side, in the pull phase, there were significant differences between the opposite side and the adjacent side in the *upper trapezius* and, in the recovery phase, differences were also found in the *upper trapezius* and *biceps brachii* (Table 2). Regarding the left paddling side, there were significant differences in the pull phase between the opposite side and the adjacent side in the *upper trapezius* and *biceps brachii*, and in the *triceps brachii* during the recovery phase (Table 3).

Table 2. Mean \pm SD of the %MVC for the comparison between the pull and recovery phases of a full stroke cycle, on the right paddling side, on the opposite and adjacent sides of the body during all five studied muscles. p-values and effect sizes are also shown.

Phases	Muscles	Opposite (% MVC)	Adjacent (%MVC)	p- Value	Cohen's D	95% CI for Cohen's D	
						Lower	Upper
Pull	<i>Upper trapezius</i>	24.35 \pm 8.75	12.28 \pm 6.98	0.01	1.53	0.66	2.36
	<i>Triceps brachii</i>	10.67 \pm 5.10	10.02 \pm 4.50	0.72	0.13	-0.61	0.87
	<i>Biceps brachii</i>	7.41 \pm 3.86	8.51 \pm 2.80	0.40	-0.33	-1.07	0.43
	<i>Tibialis anterior</i>	10.18 \pm 6.36	12.24 \pm 7.70	0.45	-0.29	-1.04	0.45
	<i>Gastrocnemius medialis</i>	10.98 \pm 4.86	8.45 \pm 4.06	0.15	0.56	-0.19	1.32
Recovery	<i>Upper trapezius</i>	14.78 \pm 6.37	10.21 \pm 5.49	0.05	0.77	-0.01	1.53
	<i>Triceps brachii</i>	33.57 \pm 17.03	32.92 \pm 16.06	0.92	0.04	-0.71	0.78
	<i>Biceps brachii</i>	4.80 \pm 2.17	8.36 \pm 5.11	0.03	-0.91	-1.68	-0.12
	<i>Tibialis anterior</i>	17.90 \pm 11.76	18.70 \pm 9.73	0.85	-0.07	-0.82	0.67
	<i>Gastrocnemius medialis</i>	10.43 \pm 4.86	10.73 \pm 6.85	0.90	-0.05	-0.79	0.69

Table 3. Mean \pm SD of the %MVC comparison between the pull and recovery phases of a full stroke cycle, on the left paddling side, on the opposite and adjacent sides of the body during all five studied muscles. P-values and effect sizes are also shown.

Phases	Muscles	Opposite (%MVC)	Adjacent (%MVC)	p-value	Cohen's D	95% CI for Cohen's D	
						Lower	Upper
Pull	<i>Upper trapezius</i>	27.60 \pm 12.65	10.77 \pm 5.68	0.01	1.72	0.83	2.58
	<i>Triceps brachii</i>	14.11 \pm 6.30	11.35 \pm 6.63	0.27	0.43	-0.33	1.17
	<i>Biceps brachii</i>	6.99 \pm 2.68	9.24 \pm 3.20	0.05	-0.76	-1.52	0.02
	<i>Tibialis anterior</i>	13.14 \pm 7.71	13.56 \pm 7.78	0.89	-0.05	-0.79	0.69
	<i>Gastrocnemius medialis</i>	10.43 \pm 5.00	9.42 \pm 3.37	0.54	0.24	-0.51	0.97
Recovery	<i>Upper Trapezius</i>	11.85 \pm 4.92	10.21 \pm 6.15	0.44	0.29	-0.46	1.04
	<i>Triceps brachii</i>	42.25 \pm 18.77	29.96 \pm 10.44	0.04	0.81	0.03	1.58
	<i>Biceps brachii</i>	6.09 \pm 4.32	9.67 \pm 7.82	0.15	-0.57	-1.31	0.19
	<i>Tibialis anterior</i>	19.59 \pm 9.89	17.67 \pm 11.09	0.63	0.18	-0.57	0.93
	<i>Gastrocnemius medialis</i>	10.12 \pm 5.52	12.04 \pm 4.91	0.34	-0.37	-1.12	0.38

Differences were found in all muscles of the upper limb and in the *tibialis anterior* on the opposite side. On the adjacent side, differences were observed only in the *triceps brachii* (Table 4). On the left paddling side, significant differences were found in the *upper trapezius* and the *biceps brachii* on the opposite side, and in the *triceps brachii* on the adjacent arm (Table 5).

Table 4. Mean \pm SD of muscle activation (%MVC) for the comparison between the pull and recovery phases on the right paddling side. *P*-values and effect sizes are also shown.

Body Side	Muscles	Pull	Recovery	<i>p</i> -Value	Cohen's D	95% CI for	
						Cohen's D	Lower
Opposite (%)	<i>Upper trapezius</i>	24.35 \pm 8.75	14.78 \pm 6.37	0.03	1.26	0.43	2.05
	<i>Triceps brachii</i>	10.67 \pm 5.10	33.57 \pm 17.03	0.01	-1.82	-2.69	-0.92
	<i>Biceps brachii</i>	7.41 \pm 3.86	4.80 \pm 2.17	0.04	0.83	0.05	1.60
	<i>Tibialis anterior</i>	10.18 \pm 6.36	17.90 \pm 11.76	0.04	-0.82	-1.58	-0.04
	<i>Gastrocnemius medialis</i>	10.98 \pm 4.86	10.43 \pm 4.86	0.77	0.12	-0.63	0.85
Adjacent (%)	<i>Upper trapezius</i>	12.28 \pm 6.98	10.21 \pm 5.49	0.39	0.33	-0.42	1.07
	<i>Triceps brachii</i>	10.02 \pm 4.50	32.92 \pm 16.06	0.01	-1.94	-2.84	-1.02
	<i>Biceps brachii</i>	8.51 \pm 2.80	8.36 \pm 5.11	0.93	0.04	-0.71	0.77
	<i>Tibialis anterior</i>	12.24 \pm 7.70	18.70 \pm 9.73	0.06	-0.74	-1.49	0.04
	<i>Gastrocnemius medialis</i>	8.45 \pm 4.06	10.73 \pm 6.85	0.30	-0.41	-1.16	0.35

Table 5. Mean \pm SD of muscle activation (%MVC) for the comparison between the pull and recovery phases on the left paddling side. *P*-values and effect sizes are also shown.

Body Side	Muscles	Pull	Recovery	<i>p</i> -Value	Cohen's D	95% CI for	
						Cohen's D	Lower
Opposite (%)	<i>Upper trapezius</i>	27.60 \pm 12.65	11.85 \pm 4.92	0.01	1.64	0.76	2.49
	<i>Triceps brachii</i>	14.11 \pm 6.30	42.25 \pm 18.77	0.01	-2.01	-2.92	-1.08
	<i>Biceps brachii</i>	6.99 \pm 2.68	6.09 \pm 4.32	0.51	0.25	-0.49	0.99
	<i>Tibialis anterior</i>	13.14 \pm 7.71	19.59 \pm 9.89	0.07	-0.73	-1.48	0.05
	<i>Gastrocnemius medialis</i>	10.43 \pm 5.00	10.12 \pm 5.52	0.88	0.06	-0.68	0.79
Adjacent (%)	<i>Upper trapezius</i>	10.77 \pm 5.68	10.21 \pm 6.15	0.80	0.95	-0.64	0.84
	<i>Triceps brachii</i>	11.35 \pm 6.63	29.96 \pm 10.44	0.01	-2.13	-3.05	-1.17
	<i>Biceps brachii</i>	9.24 \pm 3.20	9.67 \pm 7.82	0.85	-0.07	-0.82	0.67
	<i>Tibialis anterior</i>	13.56 \pm 7.78	17.67 \pm 11.09	0.27	-0.43	-1.17	0.33
	<i>Gastrocnemius medialis</i>	9.42 \pm 3.37	12.04 \pm 4.91	0.11	-0.63	-1.37	0.14

Discussion

The results of this study revealed that the participants spent more time in the recovery phase than in the pull phase. Furthermore, the muscles with the highest level of muscle activation were the *upper trapezius* and *triceps brachii* muscles of the upper limb, as well as the *tibialis anterior* muscle of the lower limb. Lastly, these findings showed that the muscles on the opposite side of the stroke had more activity than the adjacent muscles throughout the paddling cycle.

The subjects in this study spent a higher amount of time in the recovery phase (60%) compared to the pull phase (39%). This contrasts with the findings of a previous study conducted by Ruess et al., (2013b), which reported a distribution of 52% for the power phase exit, and 12.75% for the recovery phase. The differences in these results can be attributed to variations in the experience levels of the study participants, as well as the fact that Ruess et al., (2013b) used an ergometer. This laboratory setup did not consider external conditions such as water or wind that might introduce additional perturbations and instability to the paddler (Schram et al., 2019).

Upon comparing these results regarding muscle activation with those of a study conducted by Tsai et. al. (2020), it was observed that the results concerning the *upper trapezius* muscle are similar, especially when the subjects spent more time in the pull phase. This similarity was also observed in the present study in the opposite arm during left and right paddling strokes. For the *biceps brachii* muscle, the results were similar when the subjects spent more time in the recovery phase, and in this study, the muscle showed higher activation in the adjacent arm in the left and right paddling strokes. Similarly, the results for the *gastrocnemius medialis* muscles were similar when the subjects spent more time in the recovery phase and showed higher activation in the opposite and adjacent arms in the left and right paddling strokes.

However, the present study showed a difference regarding the *triceps brachii* muscle, which showed higher activation during the recovery phase than the *tibialis anterior* muscle, whereas in the study of Tsai et. al., (2020), the *triceps brachii muscle* showed higher activation during the pull phase. Trevithick et al., (2007) conducted an EMG study using a kayak ergometer and reported that during the pull phase of kayak paddling, a consistent pattern of activity was observed in the *supraspinatus*, *upper trapezius*, and *latissimus dorsi* muscles. Specifically, the *supraspinatus* muscle showed

an increase in activity from 20% to nearly 80% of the average maximum activity during the paddling cycle.

During the exit phase, a consistent pattern of activity was demonstrated in the *latissimus dorsi*, *rhomboid major*, and *serratus anterior* muscles, with this short phase of the paddling cycle oscillating between 15% and 30% of the average maximum activity. Lastly, during the recovery phase, a consistent pattern of activity was demonstrated in the *supraspinatus* and *upper trapezius* muscles. The muscles showed an initial rapid linear decrease in activity between 40% and 50% of the average maximum activity, followed by a short-duration, small increase in activity during the mid-recovery phase. The *tibialis anterior* muscle is highly activated when the ankle joint is perturbed and deviates from the normal trajectory toward plantar flexion, whereas the *gastrocnemius* is active when the ankle shows increased dorsiflexion (Tang et al., 1998).

In the current study, it was observed that the *triceps brachii* muscle in the pull phase showed higher activation in the opposite arm, regardless of whether it was during the right or left paddling stroke. Nevertheless, Tsai et al., (2020) observed that the *triceps brachii* muscle acted mainly from the later stage of the recovery phase to the middle stage of the pull phase. The difference in results can be attributed to the fact that Tsai et al., (2020) compared EMG activation in different postures, namely in the standing position, where they found higher *triceps brachii* activation.

Previous research analyzing the front crawl stroke in swimming using EMG has suggested that the scapular rotators are active throughout the paddling stroke, with the greatest activity occurring during the entry and exit phases and the lowest during the propulsive phase (Pink et al., 1991; Martens et al., 2015). In the present study, it was found that the *upper trapezius* muscle had higher activity during the recovery phase and its behavior varied depending on the paddling side. Specifically, when paddling on the left side, the *upper trapezius* exhibited higher activity in the opposite arm, while when paddling on the right side, the *upper trapezius* showed higher activity in the adjacent arm; this could be due to the fact that all of the participants were right-handed.

The *tibialis anterior*, during the pull phase, had higher muscle activation than the *gastrocnemius medialis* in the lower limbs, which contrasts with Tsai et al., (2020) findings that the *gastrocnemius medialis* was more activated in the standing position and during the pull phase, with the *tibialis anterior* reacting to the instability of the SUP board. When analyzing the upper and lower limbs together, it appears that the

lower limbs act as stabilizers, helping to balance the board during the pull phase, while the upper limbs act as propulsors. This suggests that the lower limbs may be more activated during the pull phase due to their role in stabilizing the movement of the upper limbs and the board.

Significant differences were observed in the muscle activation of all upper limb muscles during the pull and recovery phases of the paddling stroke, as well as in the *tibialis anterior* muscle of the lower limb on the opposite side (right paddling side), indicating that the muscles on the opposite side play an important role during the paddling cycle, as mentioned by Dyson et al., (1996). This could be attributed to the compensatory mechanism of the opposite side to control the oscillations and wobbling of the SUP board, as previously reported by Ruess et al., (2013a).

Several limitations need to be acknowledged in this study. Firstly, the number of stroke cycles analyzed was relatively small, which may limit the generalizability of the findings. Future studies with a larger number of stroke cycles may provide a more comprehensive understanding of the impact of fatigue on paddling mechanics. Secondly, this study did not analyze the role of core muscles in the paddling stroke cycle, which can be an important factor in the development of fatigue. Incorporating core muscle analysis into future studies may provide a more holistic view of the effects of fatigue on paddling mechanics. Finally, the sample population consisted of recreational paddleboarders, which may not reflect the experiences of more experienced paddleboarders. It would be beneficial to recreate this study with a more diverse sample, including both experienced and inexperienced paddleboarders to better understand the impact of fatigue on paddling mechanics at different levels of expertise.

A better understanding of the role of upper and lower body muscles during the paddling stroke can be valuable for paddleboarders looking to improve their conditioning and technique.

The findings of this study suggest that training programs should be designed considering that stimulation of opposite and adjacent muscles depends on the side of the paddling stroke and stroke phases. Considering that the development of force applied in the propulsive and recovery phases can improve muscle recruitment, coaches and athletes should consider the importance of switching movements between the two sides of the stroke and in this way, promote balance in muscle recruitment. Therefore, incorporating these recommendations into a comprehensive training regimen can potentially improve overall paddling performance.

Conclusions

The findings of the current study indicate that the muscles on the opposite side of the paddle exhibited higher activity compared to the muscles associated with the paddle side. In SUP, athletes can choose to alternate the paddling side for technical or tactical reasons. Instructors can observe the performance of SUP practitioners and recommend switching movements to promote muscle balance and reduce muscle fatigue on the paddling side. These observations and recommendations can be easily incorporated into SUP training programs to improve overall paddling efficiency and reduce the risk of injury.

Study 3. The influence of kinematics and neuromuscular activity on stand-up paddling performance using cluster analysis

Abstract

This study classified stand-up paddle (SUP) practitioners by using cluster analysis of kinematic and neuromuscular activity. 14 male paddleboarders (24.2 ± 7.1 yrs) performed 3 submaximal trials of 65-m. Surface electromyography of *upper trapezius* (UT), *biceps brachii* (BB), *triceps brachii* (TB), *tibialis anterior*, and *gastrocnemius medialis*, on both sides of the body. Speed, stroke frequency, distance per stroke, and stroke index (SI) were also assessed. Clusters were discriminated between performances in different groups according to speed ($F = 4.24$, $p = 0.043$, $\eta^2 = 0.44$). The left UT of the left pull ($F = 7.20$, $p = 0.010$, $\eta^2 = 0.57$), the right TB of the left recovery ($F = 6.21$, $p = 0.016$, $\eta^2 = 0.53$), and the right TB of the left pull ($F = 5.80$, $p = 0.019$, $\eta^2 = 0.51$) were the main variables of the clusters. Best performers were characterised by high activations of the left UT during the left pull and the left TB during the right recovery, along with greater SI. Poor performers displayed low activations of right TB during the pull and recovery phases. Better performers showed high activations, in UT and TB during the pull and recovery phases, emphasising their role in SUP performance.

Keywords: Movement pattern, biomechanics, electromyography, performance

Introduction

Stand-up paddle (SUP) is characterised by elements of surfing and paddle sports (Furness et al., 2017) and therefore involves multifactorial interactions across scientific domains (Mendez-Villanueva & Bishop, 2005). In recent years, research has tended to elucidate various aspects related to the physiological, musculoskeletal, and psychological effects of SUP, as well as its performance analysis (Furness et al., 2017; Schram, Hing, & Climstein, 2017; Schram, Hing, Climstein, & Furness, 2017; Willmott et al., 2020). For example, SUP races appear to involve a high aerobic demand and a significant impact of tactical decisions on variations in distance covered, peak speed, and heart rate (Schram, Hing, Climstein, & Furness, 2017). Indeed, elite SUP athletes have aerobic power levels comparable to other upper limb- dominant water-based sports (Schram et al., 2016a). The importance of technique for SUP performance was also highlighted (Schram et al., 2019). It was found that experienced paddlers tend to use different paddle stroke kinematics than inexperienced, relying less on shoulder range of motion and more on hip motion (Schram et al., 2019). Although the literature suggests that a combination of physiological, tactical, and technical factors may contribute to SUP performance, the study of performance and its determinants in SUP remains scarce (Castañeda-Babarro et al., 2022).

Identifying and predicting key determinants is common in other aquatic sports (e.g. López-Plaza et al., 2017; Morais et al., 2021). For example, energetics, anthropometrics, kinematics, and efficiency have been proposed as some of the main factors responsible for the variation in technique and performance in swimming (Morais et al., 2021; Silva et al., 2019; Zacca et al., 2018). Furthermore, the greater performance of highly trained kayakers and canoeists was found to be associated with superior physical fitness and body size (López- Plaza et al., 2017), while stroke parameters (i.e. speed fluctuations, propulsive forces, drag forces, paddling stroke rates) and velocity changes are important variables in predicting the paddling time in kayakers (Freitas, Conceição, Louro, et al., 2023; Gomes et al., 2022; Michael et al., 2009). Indeed, in sports such as rowing, kayaking, and swimming, stroke kinematics play a fundamental role in technique/mechanics and performance variability (Ettema et al., 2022; Gomes et al., 2022; Morais et al., 2014). For instance, being able to increase the stroke rate is important for enhancing race time and performance (Gomes et al., 2022). To do that, previous studies have demonstrated the importance of neuromuscular factors, such as force production, coordination, and activation patterns (Akbar et al., 2022; Gomes et al., 2015; Morais et al., 2021). Therefore, we can suggest that SUP performance

depends on stroke kinematics, and understanding the influence of neuromuscular activity will be essential. However, the applicability of these findings to SUP remains uncertain given the unique biomechanics and environmental conditions of SUP.

While the existing literature has shed light on the multifactorial nature of performance in several aquatic sports, SUP presents unique challenges that require further investigation (Castañeda-Babarro et al., 2022; Freitas, Conceição, Šťastný, et al., 2023; Willmott et al., 2020). Despite the progress made in SUP research, there is still a need to understand the neuromuscular and biomechanical determinants that influence performance (Freitas, Conceição, Šťastný, et al., 2023; Tsai et al., 2020). By addressing this gap, the present research contributes to the existing body of knowledge but also has implications for SUP athletes, allowing for further understanding of the factors that can maximise their potential. Therefore, the purpose of this study was to classify and identify SUP performance based on kinematics and neuromuscular activity patterns by cluster analysis. This will allow us to understand which variables are related to better and poorer performances. It was hypothesised that the interplay between different variables would be responsible for the cluster formation, and not only variables from a specific domain.

Materials and Methods

Participants

Fourteen male recreational SUP participants, all right-handed, volunteered for this study (age: 24.2 ± 7.1 years, height: 1.73 ± 1.22 m, body mass: 58 ± 15.5 kg, wingspan: 1.79 ± 0.87 ; mean \pm SD). Inclusion criteria included age requirements (>18 years), a minimum of 6 months of regular SUP experience (1–2 times per week), and were excluded if they had any health risks or conditions that affected paddling performance. Prior to testing, the participants were informed of the procedures and signed an institutionally approved written informed consent. This study was approved by the University Ethics Committee (CE-UBI-Pj-2022–042) and all the procedures were in accordance with the Declaration of Helsinki regarding human research.

Design and Procedures

In this cross-sectional study, each participant performed three stand-up paddling trials at individual submaximal speed (i.e. at 75% of predicted maximal heart rate) during which kinematic (i.e. speed, stroke frequency [SF], distance per stroke [DPS], and stroke index [SI]) and neuromuscular activity (i.e. surface electromyography [EMG] of

the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis*) were measured.

All data were collected using the same paddleboard model (SUP Board Itiwit 10'32"5') and paddle (Itwit 170-220 cm). Before each trial, the height of the paddle was adjusted independently for each participant within a range of 1.7–2.2 m (Willmott et al., 2020). Trials were conducted in the same location, in calm water, free of current disturbance, and in a downwind direction. Wind speed was recorded daily and the average wind speed during the trials was 3.4 m/s (light breeze) as measured on the Beaufort Wind Scale and confirmed by the National Weather Service (2022). After a self-selected warm-up of 5 min, each participant completed a 65 m trial in a straight line, demarcated by two floaters indicating the start and end of the trial (Freitas, Conceição, Louro, et al., 2023). To maintain forward motion while paddling, participants were instructed to switch paddle sides after three strokes (Tsai et al., 2020). Participants were instructed to perform the trials at a moderate pace between 70 and 75% of the predicted maximum heart rate (Shookster et al., 2020). To ensure participants maintained their heart rate within the prescribed threshold, a familiarisation session was conducted before the test, where participants trained at a submaximal speed approximating 75% of their predicted maximum heart rate. During the test, participants controlled their heart rates using a Suunto Smartwatch 9 Peak along with the Suunto Smart Heart Rate Belt (Suunto, Vantaa, Finland), which continuously monitored their heart rates in real-time. If deviations from the target range occurred, participants adjusted their paddling intensity accordingly.

Neuromuscular Analysis

Muscle activity on both sides of the body was assessed by surface EMG using a wireless system with built-in accelerometers (Miniwave, Cometa, Milano, Italy;

EMGandMotionsTools software 8.7.6.0) and probes equipped with a 7-g memory and a sampling rate of 2000 hz at 16 bits. To ensure accurate measurements, the skin was first gently shaved, rubbed with sandpaper, and cleaned with alcohol, following the protocol outlined by Afsharipour et al. (2019). This was done to prevent the interelectrode resistance from exceeding 5 KOhm. To protect the electrodes from water interference, transparent bandages with labels (Hydrofilm®, 10 cm x 12.5 cm, U.S.A.) were used to cover the electrodes as recommended (Hohmann et al., 2006). In addition, participants wore custom-made long-sleeved surfing suits (Decathlon, Olaiian 3/2 mm, Villeneuve-d'Ascq, France) to protect the electrodes and sensors during the trials. EMG sensors (Kendall™, ECG electrodes, 57 × 34 mm, 57 width mm × 34 length

mm, gel area 201 mm², sensor area 80 mm², Dublin, Ohio, U.S.A.) were placed according to the SENIAM recommendations (Hermens et al., 2000) to analyse the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis* muscles (Figure 1). These muscles were selected due to their importance in SUP (Ruess et al., 2013; Tsai et al., 2020).

Prior to the study evaluation, each subject performed three maximal voluntary isometric contractions for each muscle studied on dry land to assess the maximum voluntary contraction (MVC). The contractions were held for 5 seconds, followed by 5 minutes of rest, and verbal encouragement was given to the subjects. The maximum value of the three measurements was used to normalise the EMG signals (Boettcher et al., 2008; Hermens et al., 2000). MVC procedures were performed using the manual resistance applied by the examiner and according to the guidelines of the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) and Noraxon (Scottsdale, Arizona, U.S.A.) companies (Al-Qaisi & Aghazadeh, 2015; Dyson et al., 1996). The detailed procedures for MVC assessment for each muscle can be found



Figure 1. Participant equipped with surface electromyography electrodes.

in a previous study by Freitas, Conceição, Šťastný, et al. (2023). The maximum value of the resulting EMG was determined and averaged across the trials for each test.

During the trials, the EMG measurement was synchronised with a digital video camera (Panasonic, DC-FZ 1000II, Osaka, Japan) mounted on a tripod (Falcon Eyes, FT-120, Hoogeveen, The Netherlands) perpendicular to the course at a distance of 20 metres. To synchronise the data, the subjects had to stand on the board in a T-position for 5 seconds and then tap on their arm *biceps brachii* three times before starting the trials. Each video was edited according to the trials and then the data was synchronised with the EMG software (EMG and Motion Tools, V8, Cometa, Bareggio Mi, Italy). The pull and recovery phases of the stroke were determined as previously reported elsewhere (Freitas, Conceição, Šťastný, et al., 2023; Michael et al., 2009; Tsai et al., 2020). To ensure accuracy, event times were verified by a second observer, which increased the reliability of the measurements associated with the different phases performed by the upper limb. The first six cycle strokes of both sides were excluded from the analysis, as well as the first stroke of each cycle, to eliminate paddle transfer from side to side, which affects the cycle parameters. Four left and four right cycle strokes were then analysed.

Signal processing was initiated by filtering the MVC file. The EMG sensors received raw EMG data that was filtered using a low-pass filter with a cut-off frequency of 400 hz and a 4th order Butterworth filter, and a high-pass filter with a cut-off frequency of 20 hz and a 4th order Butterworth filter. After signal rectification, a smoothing technique was applied using a Root Mean Square envelope with a 50 ms window. The maximum MVC activation values (μV) were then calculated for each muscle and presented as percentage MVC (% MVC). Finally, the last processing step involved applying the same filters to the signal obtained from each trial and applying the MVC to the trial file.

Kinematics Analysis

The same cycle strokes used for EMG analysis were used for the kinematic evaluation. After image acquisition, during the subsequent analysis phase, the Kinovea [®] software (version 0.9.5) was used for video editing, duration registration, and kinematic analysis based on sagittal plane images. The choice of the sagittal plane was motivated by its ability to provide a comprehensive view of the paddling motion, considering the kinematic characteristics of the paddling motion. As shown above, four cycle strokes were analysed for both the left and right sides of each subject. The use of Kinovea [®] software for kinematic analysis is well supported by previous research, which has demonstrated its accuracy in frame- by-frame video analysis and its strong agreement with other motion capture systems in various sports applications, including paddling

and stroke analysis (e.g. Fernandes et al., 2024; Fernández-González et al., 2020). The kinematic parameters analysed were calculated as follows: speed was derived as distance divided by time, SF (in Hz) as the number of cycles per second, DPS (in m) as the total distance divided by the number of strokes, and SI (in m²/s) as the product of DPS and speed, providing comprehensive scientific support for performance assessment (Abellán-Aynés et al., 2023).

Statistical Analysis

Normality of data distribution was analysed using the Shapiro-Wilk test. The mean and standard deviation were calculated as descriptive statistics. Cluster modelling was performed based on the k-means approach (non-hierarchical). This allows the definition of several clusters to be used in advance. The k-means defines a centroid (i.e. the mean of a group of points/subjects) based on their similarities (Rein et al., 2010). Standardised z-scores were used to ensure consistent comparison of data sets with different magnitudes and/or units. All variables were tested in the modelling, except those related to EMG. For these, the correlation between speed and muscle activity was first verified with the Spearman correlation coefficient ($p < 0.05$). The variables that showed a significant correlation were tested in the cluster modelling. One-way ANOVA was used to identify the main determinants responsible for the formation of the clusters ($p < 0.05$). The total eta-squared (η^2) was chosen as the effect size index and was considered as: (i) no effect if $0 < \eta^2 < 0.04$; (ii) minimal if $0.04 < \eta^2 < 0.25$; (iii) moderate if $0.25 < \eta^2 < 0.64$ and; (iv) strong if $\eta^2 > 0.64$ (Ferguson, 2009). Bonferroni post-hoc correction ($p < 0.017$) was used to identify differences between clusters whenever suitable. The significance level was set at $\alpha = 0.05$. Stepwise discriminant analysis was used to validate the clusters.

Results

The elbow method was used to test several cluster solutions (from 2 to 9), where the three-cluster solution presented the highest power. Cluster 1 was labelled as the cluster with poor performances, cluster 2 with medium performances, and cluster 3 with best performances. Participants maintained trial intensity around 75% of the predicted maximum heart rate, with no differences between clusters (cluster 1: 140.50 ± 42.23 bpm; cluster 2: 148.80 ± 3.90 bpm; cluster 3: 139.40 ± 13.67 bpm; $F = 0.230$, $p = 0.798$, $\eta^2 = 0.00$). Table 1 presents the descriptive and inferential data of the variables tested after the cluster modelling. Speed ($F = 4.24$, $p = 0.043$, $\eta^2 = 0.44$) presented significant differences between clusters. The left *upper trapezius* of the left pull ($F = 7.20$, $p = 0.010$, $\eta^2 = 0.57$), the right *triceps brachii* of the left recovery ($F = 6.21$, $p = 0.016$, $\eta^2 = 0.53$), and the right *triceps brachii* of the left pull ($F = 5.80$, $p = 0.019$, $\eta^2 = 0.51$) were the main variables responsible for the formation of the clusters. Cluster 1 (poor performers) was characterised by low activations of the right *triceps brachii* during the left pull, right *triceps brachii* during the left recovery, and right *triceps brachii* during the right pull. Cluster 2 (medium performers) was characterised by a small DPS, and large activations of the right and left *triceps brachii* during the left pull. Cluster 3 (best performers), besides the fast speeds, was also characterised by large activations of the left *upper trapezius* during the left pull, a greater SI, and large activations of the left *triceps brachii* during the right recovery.

Stepwise discriminant analysis was used as a qualitative assessment of clustering. This extracted two functions including the left *upper trapezius* of the left pull and the right *triceps brachii* of the left pull. Function 1 was mainly defined by the left *upper trapezius* of the left pull explaining 84.6% of the variance ($\Lambda = 0.203$, $X^2 = 16.722$, $p = 0.002$). Function 2 was mainly defined by the right *triceps brachii* of the left pull explaining 15.4% of the variance ($\Lambda = 0.695$, $X^2 = 3.821$, $p = 0.051$). The discriminant analysis

Table 1. Descriptive (mean \pm SD – standard deviation) and clustering statistics.

	Cluster 1 (N = 4)		Cluster 2 (N = 5)		Cluster 3 (N = 5)		F-ratio (p)	η^2
	Mean \pm SD	z-score	Mean \pm SD	z-score	Mean \pm SD	z-score		
Speed [m/s]	1.07 \pm 0.19	-0.5931	1.16 \pm 0.16	-0.1605	1.45 \pm 0.18	1.1654	4.24 (0.043)	0.44
SF [Hz]	0.55 \pm 0.10	-0.8342	0.70 \pm 0.13	0.3377	0.69 \pm 0.06	0.3242	2.35 (0.141)	0.30
DPS [m]	1.96 \pm 0.20	0.3588	1.69 \pm 0.18	-0.5824	2.11 \pm 0.40	0.8805	3.68 (0.060)	0.40
SI [m²/s]	2.10 \pm 0.46	-0.2130	1.96 \pm 0.29	-0.4231	3.09 \pm 0.95	1.2713	5.14 (0.026)	0.48
Right pull [%MVC]								
Left <i>Upper trapezius</i>	23.92 \pm 13.62	-0.0493	23.39 \pm 7.19	-0.1093	27.15 \pm 6.95	0.3207	0.17 (0.841)	0.03
Left <i>Triceps brachii</i> ^b	6.46 \pm 1.61	-0.8224	11.48 \pm 5.65	0.1613	14.33 \pm 3.38	0.7202	2.85 (0.100)	0.34
Right <i>Triceps brachii</i>	5.92 \pm 2.87	-0.9106	11.93 \pm 4.69	0.4247	11.02 \pm 2.30	0.2231	3.14 (0.083)	0.36
Right <i>Biceps brachii</i>	5.97 \pm 1.29	-0.9019	8.73 \pm 2.49	0.0817	11.34 \pm 2.20	1.0119	5.29 (0.025)	0.49
Right recovery [%MVC]								
Left <i>Triceps brachii</i> ^a	27.20 \pm 17.15	-0.3732	28.58 \pm 14.91	-0.2923	53.66 \pm 1.84	1.1798	3.82 (0.055)	0.41
Right <i>Triceps brachii</i> ^c	18.71 \pm 10.07	-0.8853	36.95 \pm 16.61	0.2505	42.49 \pm 9.84	0.5959	3.05 (0.088)	0.36
Left pull [%MVC]								
Left <i>Upper trapezius</i>	6.41 \pm 2.77	-0.7667	10.14 \pm 4.32	-0.1114	18.05 \pm 4.79	1.2823	7.20 (0.010)	0.57
Left <i>Triceps brachii</i>	5.88 \pm 3.05	-0.8240	14.63 \pm 7.06	0.4949	10.97 \pm 4.92	0.0562	2.85 (0.100)	0.34
Right <i>Triceps brachii</i>	7.33 \pm 3.30	-1.0752	17.39 \pm 6.00	0.5225	15.45 \pm 0.97	0.2143	5.80 (0.019)	0.51
Left <i>Biceps brachii</i>	6.51 \pm 3.09	-0.8513	9.62 \pm 2.85	0.1217	11.95 \pm 1.15	0.8511	3.63 (0.061)	0.40
Left recovery [%MVC]								
Left <i>Triceps brachii</i>	20.61 \pm 5.48	-0.8949	34.17 \pm 11.68	0.4046	32.55 \pm 2.56	0.2490	2.94 (0.094)	0.35
Right <i>Triceps brachii</i>	23.20 \pm 16.23	-1.0145	45.72 \pm 14.38	0.1854	59.51 \pm 7.64	0.9201	6.21 (0.016)	0.53

SF – stroke frequency; DPS – distance per stroke; SI – stroke index; HR – heart rate; %MVC- percentage of maximal voluntary contraction; η^2 – eta square (effect size index). Superscripts: a – post-hoc differences between cluster 1 and 3; b – post-hoc differences between cluster 1 and 3.

showed a good compactness/separation with a correct classification of the original groups (71.4%) and a correct classification of the cross-validated groups (71.4%) (Figure 2). The following classification functions are available:

$$\text{Cluster 1} = -4.340 + (0.432 \cdot R \text{ Triceps LP}) + (0.516 \cdot L \text{ Upper Trapezius LP}) \quad (1)$$

$$\text{Cluster 2} = -13.936 + (0.954 \cdot R \text{ Triceps LP}) + (0.896 \cdot L \text{ Upper Trapezius LP}) \quad (2)$$

$$\text{Cluster 3} = -21.075 + (0.972 \cdot R \text{ Triceps LP}) + (1.381 \cdot L \text{ Upper Trapezius LP}) \quad (3)$$

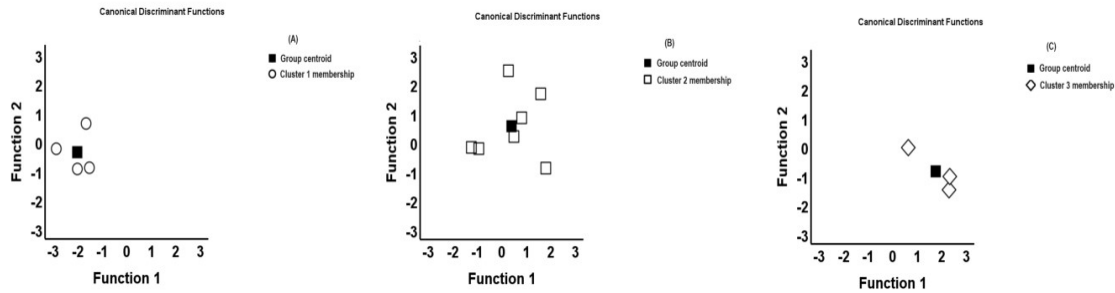


Figure 2. Territorial map for each cluster. Panel (A) – cluster 1; Panel (B) – cluster 2; Panel (C) – cluster 3.

Where R Triceps LP is the right *triceps brachii* activation during the left pull (in % MVC), and L Upper Trapezius LP is the left *upper trapezius* activation during the left pull (in % MVC).

Discussion

The purpose of this study was to classify and identify SUP performance based on kinematics and neuromuscular activity patterns by cluster analysis. The results showed that the clustering adequately discriminated the performances between the different groups according to speed. Faster performances were associated with unique neuromuscular activation patterns during the pull and recovery phases, as well as higher speeds. Furthermore, the determinants that characterised each cluster were different according to the speed of the trials.

The cluster analysis allowed us to distinguish between the speed of the participants clearly, and in this way, it was possible to identify the variables that characterised each group, particularly neuromuscular activity in different muscles and kinematic factors. Previous findings have shown some differences between experienced and inexperienced paddlers, suggesting that those with better performance used a more efficient SUP stroke, possibly due to a larger catch angle and longer stroke length, resulting in higher peak power output (Brown et al., 2011; Schram et al., 2016b, 2019).

In this study, the best performers were distinguished by significant muscle activations and higher stroke indices. Specifically, these individuals demonstrated large activations of the left *upper trapezius* during the left pull and the left *triceps brachii* during the right recovery, in addition to higher speed and SI values. These findings highlight the interplay between muscle activation and kinematic efficiency in achieving optimal SUP performance. In contrast, the poor performers showed lower activations of key muscles during both the pull and recovery phases, including the right *triceps brachii* during the left pull, the right pull, and the right recovery phases. This insufficient muscle engagement during key phases of the stroke cycle indicates possible inefficiencies in force production and coordination, which may limit performance.

Increased activation of the left *upper trapezius* during the left pull likely helps create a more efficient stroke by stabilising the shoulder and reducing energy loss. This contributes to the higher speeds and SI values observed in the best performers. Additionally, the *triceps brachii* plays a key role in extending the arm during the recovery phase of a stroke, which prepares the paddle for the next stroke. This activation supports arm extension, torso twisting, and preparation for force application during the pull. Increased activation during these phases improves stroke efficiency by ensuring proper positioning (Tsai et al., 2020). Higher activation in this muscle during the recovery phase ensures that the paddler positions the paddle quickly and effectively, reducing cycle time while maintaining stroke efficiency (Freitas, Conceição, Šťastný, et al., 2023). This activation of the contralateral *triceps brachii* (left triceps during right recovery) may reflect advanced coordination and timing among opposing muscle groups, which is often seen in skilled athletes (Schram et al., 2016a).

Interestingly, the poor and medium performers displayed low muscle activation during the pulling phase, suggesting that inefficiencies in this phase contribute significantly to slower speeds. In contrast, the recovery phase played a decisive role for the best performers, with high muscle activity during this phase supporting better stroke preparation and overall efficiency. Therefore, the attention to the recovery phase and the work of the muscles during this phase of the stroke should not be neglected. This is even more important as it is known that the recovery phase can take up the majority of the stroke time in SUP (Freitas, Conceição, Šťastný, et al., 2023).

According to the stepwise discriminant analysis, the formation of the clusters could be resolved by including the data from the right *triceps brachii* activation and left *upper trapezius* during the left pull. This means that information about these variables allows accurate classification of participants into the faster, medium, or slower group of paddlers. *Triceps brachii* and *upper trapezius* activity, particularly during the left pull

and recovery phases, emerged as a consistent determinant across analyses, highlighting its critical role in SUP performance.

Although research on this topic is scarce, and this was the first study to use cluster analysis to examine neuromuscular activity and kinematics in SUP, some limitations must be acknowledged. The participants were recreational paddleboarders, which may not reflect the results of more experienced SUP athletes. It would be beneficial to replicate this study with different participants and genders to better understand the differences and determinants of SUP performance. This should also be understood when maximal effort is required. Additionally, expanding the analysis to include more muscles would provide a deeper understanding of performance variability in SUP. Despite these challenges, the contributions of this research are noteworthy and point the way for future research in SUP.

Conclusion

This study used clustering modelling to categorise and identify SUP practitioners into subgroups based on performance, differentiating between faster, medium, and slower performers, and examining how neuromuscular activation and kinematics affect performance. One of the key findings of this research is that faster SUP performers were characterised by higher speed and greater SI, coupled with specific neuromuscular activation patterns during both the pull and recovery phases of the stroke. The determinants that characterised each cluster were distinct and highlighted critical neuromuscular contributions to performance variability. Among the muscles analysed, the main variables influencing the formation of clusters were the low activations of muscles during the pull and recovery phases for poor performers (*triceps brachii*), and large activation for the best performers (*upper trapezius* and *triceps brachii*). The stepwise discriminant analysis further reinforced the significance of specific muscle activations, particularly the left *upper trapezius* during the left pull and the right *triceps brachii* during the left pull, as key predictors for differentiating between performance groups. These findings emphasise that neuromuscular engagement, especially during the pull phase, along with effective preparation for the recovery phase, is crucial for achieving higher SUP performance. The implications of this study extend beyond the academic context to help SUP practitioners and coaches optimise technique and SUP performance by further understanding performance variability and its biomechanical determinants.

Study 4. Kinematic and Neuromuscular Responses to Different Visual Focus Conditions in Stand-Up Paddleboarding

Abstract

This study analyzed the kinematics and muscle activity during the stand-up paddle (SUP) under different visual focus points in three conditions: i) eyes on the board nose, ii) looking at the turn buoy, and iii) free choice.

Fourteen male paddleboarders (24.2 ± 7.1 years) performed three trials covering 65 m, and the electromyographic (EMG) activation patterns and kinematic parameters in 4 cycle strokes for the left and right sides were analyzed. Surface EMG of the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis* were recorded. The data were processed according to the percentage of maximum voluntary contraction (%MVC). Speed, stroke frequency (SF), stroke length, and stroke index (SI) were analyzed.

The speed, SF, and SI ($p < 0.01$, $\eta^2 \geq 0.42$) showed significant variance between conditions, with the free condition achieving the highest speed (1.20 ± 0.21 m/s), SF (0.65 ± 0.13 Hz) and SI (2.25 ± 0.67 m²/s). This condition showed greater neuromuscular activity, particularly in the *triceps brachii* during both the left (42.25 ± 18.76 %MVC) and right recoveries (32.93 ± 16.06 %MVC). During the pull phase, the free choice presented higher *biceps brachii* activity (8.51 ± 2.80 %MVC) compared to the eyes on the board nose (6.22 ± 2.41 %MVC; $p < 0.01$), while showing lower activity in the *triceps brachii* (10.02 ± 4.50 %MVC vs. 16.52 ± 8.45 %MVC; $p < 0.01$) and *tibialis anterior* (12.24 ± 7.70 %MVC vs. 17.09 ± 7.73 %MVC; $p < 0.01$) compared to looking at the turn buoy.

These results suggest that a free visual focus allows paddleboarders to enhance their kinematics and muscle activation, highlighting the significance of visual focus strategies in improving both competitive and recreational SUP performance.

Keywords: SUP, muscle activation, EMG, attentional focus, recreational practitioners.

Introduction

Stand-up paddle boarding (SUP) has spiked in popularity over the last decade (Hibbert et al., 2023; Neiva et al., 2020), and this can be primarily attributed to its relatively easy learning curve (Schram et al., 2016b; Waydia & Woodacre, 2016). Unlike traditional surfing, SUP uses a larger board and a paddle, offering superior buoyancy, greater stability, and enhanced stroke efficiency. Upper-body strength, lower-body stabilization, and core muscle activity work in synergy to create forward movement during SUP (Ruess et al., 2013a; Schram et al., 2016a). This way, each stroke involves the activation of different muscles, such as the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis* (Freitas et al., 2023; Ruess et al., 2013a; Tsai et al., 2020). An optimal contribution of these muscle groups is needed to ensure stroke efficiency and balance (Ruess et al., 2013a; Schram et al., 2016a).

As scientific interest in SUP continues to grow worldwide, there is a need to understand the biomechanical factors that can potentially influence paddling performance (Freitas et al., 2023; Neiva et al., 2020; Ruess et al., 2013a; Tsai et al., 2020). Kinematic analysis is important for performance assessment, as it provides insights into stroke mechanics, efficiency, and optimal movement patterns, ultimately influencing speed (Abellán-Aynés et al., 2023; Vaquero-Cristóbal et al., 2013; Abellán-Aynés et al., 2024). According to earlier research on sprint kayaking and canoeing, it seems to be important to maintain a steady stroke rate for best results because variations might lead to inconsistent propulsion and lower efficiency (Goreham et al., 2021). Inter-stroke steadiness is a key determinant of paddling performance in sprint canoeing, with faster race timings being associated with higher steadiness (Abellán-Aynés et al., 2024). Furthermore, the change of key kinematic variables such as stroke frequency (SF), stroke length (SL), and stroke index (SI) has been shown to impact performance (Vaquero-Cristóbal et al., 2013). Although not commonly reported as other kinematic measures, SI is an important efficiency metric that reflects an athlete's ability to maintain velocity with an optimal stroke length in swimming (Barbosa et al., 2010; Morais et al., 2021). Research in sprint kayaking has demonstrated that SI follows a similar trend, peaking early in a race and then declining due to fatigue-related reductions in velocity and stroke efficiency (Vaquero-Cristóbal et al., 2013). Thus, SI can provide valuable insights into the efficiency of SUP by measuring the effectiveness of each stroke under different conditions (Abellán-Aynés et al., 2023; Vaquero-Cristóbal et al., 2013).

While kinematic factors are essential for paddling efficiency, neuromuscular activation patterns also seem to affect stroke performance and technique. Previous research has found different electromyographic (EMG) activation patterns during the paddling stroke cycle (Freitas et al., 2023) and when adopting different postures on the board, such as when standing or kneeling (Tsai et al., 2020). Furthermore, studies suggested that paddlers with better performance demonstrate a more efficient SUP stroke than their poorer performance counterparts, possibly due to a more prominent catch angle and longer stroke length and a higher peak power output (Brown et al., 2011; Schram et al., 2016a, 2019). Since kinematic variables influence stroke efficiency, understanding the interplay between attentional focus and movement execution could be important for optimizing SUP technique.

In addition to the biomechanical factors mentioned earlier, attentional focus significantly influences motor performance and learning across various fields, including precision tasks in surgery and sports skills (Bull et al., 2023; Neumann, 2019). Attentional focus—beyond just visual focus—determines how motor resources are allocated, which in turn could affect paddling efficiency. Previous research has demonstrated that directing attention to different aspects of the movement, such as body segments or external objects, can lead to distinct movement patterns and muscular activation strategies (Bull et al., 2023; Neumann, 2019). For instance, Bull et al. (2023) found that an external focus of attention enhances technique in skilled cricket batters, while Neumann (2019) observed that an external attentional focus benefits the movement economy in weightlifters by promoting automatic motor control. However, the influence of attentional focal points on movement patterns and neuromuscular activation during SUP has received limited attention in scientific literature. In the context of SUP, the paddlers may focus on the nose of the board, a turn buoy, or maintain a free gaze across the water, and these choices may influence the paddler's perception, decision-making, and motor execution, shaping their movement patterns and muscle activation strategies.

In the learning process, SUP techniques enhance balance on the board (Ruess et al., 2013b), often requiring paddlers to focus on an object or the coastline while paddling. However, there is a gap in research concerning how changes in the attentional focus affect kinematic and muscular participation during SUP performance. Therefore, this study aimed to assess the kinematic and neuromuscular activation in SUP under different attentional focus conditions through visual fixation points. We hypothesize that different attentional orientations could lead to distinct muscle activation levels and kinematic changes in SUP practitioners, ultimately influencing paddling performance across different sides of the stroke cycle.

Materials and Methods

Participants

Fourteen recreational right-handed male SUP participants (24.0 ± 7.1 years, 1.73 ± 1.22 m, 58.2 ± 15.5 kg, wingspan 1.79 ± 0.87 m, and body mass index 24.2 ± 4.9 kg/m²) volunteered to participate in this study after being instructed on the procedures. Due to the exploratory nature of this study and the effect sizes observed in similar research (e.g., Freitas et al., 2023, Tsai et al., 2020), a minimum of 12–15 participants should be appropriate to ensure statistical power while keeping data collection and analysis feasible. Nevertheless, a priori power analysis was conducted using G*Power 3.1 software, with a moderate effect size ($\eta^2 = 0.25$), an alpha level of 0.05, and a power of 0.80, which indicated that a minimum of 12 participants would be sufficient for detecting meaningful differences. Participants were only included if they were ≥ 18 years old and had at least six months of SUP experience with regular practice (1–2 times per week). Participants were excluded if they had any medical conditions, injuries, or impairments that could affect paddling performance or compromise their safety. Given this inclusion criterion, the sample consisted of recreational athletes with relatively stable training loads, minimizing the influence of individual training volume and intensity on the study outcomes. Before testing, the participants were informed about the benefits and risks of the investigation and signed an institutionally approved informed consent document. This study was approved by the University of Beira Interior Ethics Committee (CE-UBI-Pj-2022-042), and all the procedures followed the Declaration of Helsinki regarding human research.

Study Design

Before initiating the official trials, each subject performed a 5-minute warm-up at a self-selected frequency and intensity while becoming familiar with the equipment (SUP board Itiwit 10'32"5', paddle Itwit 170-220cm). The protocol was performed on an inland lake with no current interference, and the participants had to paddle in a straight line (Figure 1). Before starting data collection, the temperature and wind conditions were analyzed to determine the feasibility of conducting the trials without interference from external factors. All trials were conducted in calm water, free from current interference. All trials were carried out in the wind direction, and daily recordings were obtained, yielding an average wind speed of 3.4 m/s (Gentle Breeze)

according to the Beaufort Wind Scale (National Weather Service, 2022). Each participant was asked to remain in a bipedal position and start paddling parallelly along a straight line marked with a length of 65 meters. This area was demarcated with starting and finishing points and a boundary rope running its entire length.

In this cross-sectional study, each participant performed three stand-up paddling trials, each under a different focus condition, presented in randomized order: i) Condition #1: eyes on the board nose (the participant focused their gaze on the front of the board throughout the trial); ii) Condition #2: looking to the turn buoy (the participant directed their gaze at the buoy, marking the paddling distance's endpoint); iii) Condition #3: free (the participant paddled without a predetermined focal point, allowing for natural gaze behavior) in random order. Each testing session was conducted within a single day per participant, with all trials completed in a 3-hour window to minimize the potential of environmental fluctuations. Participants were tested individually to maintain consistent environmental conditions and minimize external distractions. A 30-minute passive rest period was maintained between each of the three trials to prevent fatigue from affecting performance.

To standardize paddling intensity, participants were instructed to maintain a comfortable, submaximal speed approximating 70% of their predicted maximum heart rate (Shookster et al., 2020). Heart rate was continuously monitored using the Suunto Smartwatch 9 Peak with a Suunto Smart Heart Rate Belt (Suunto, Vantaa, Finland), ensuring that paddling intensity remained between 70% and 75% of maximum heart rate throughout all trials. Data confirmed that there were no significant differences in heart rate across conditions (Condition #1: 138.7 ± 16.3 bpm; Condition #2: 141.1 ± 16.9 bpm; Condition #3: 140.6 ± 17.8 bpm; $F = 1.26$, $p = 0.30$, $\eta^2 = 0.09$), indicating consistent effort levels between trials.

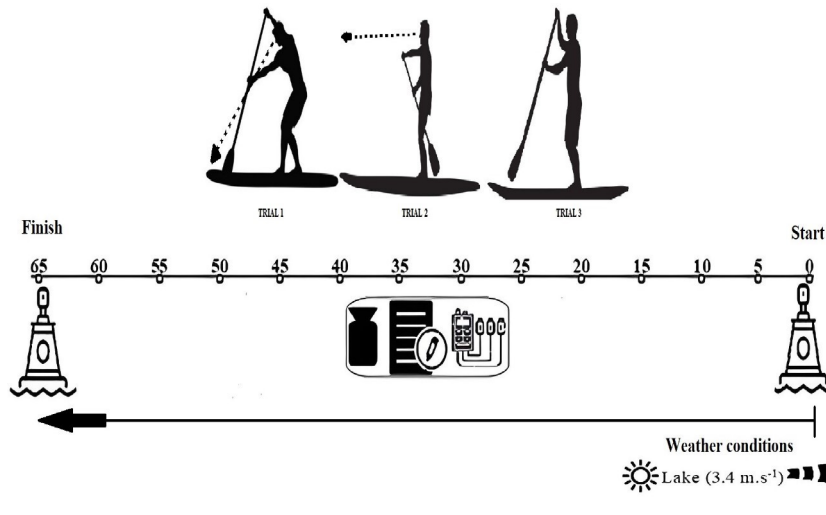


Figure 1. Scheme of the Field Data Collection Protocol of 3 trials in 3 different conditions of execution: Trial 1 (Condition #1): eyes on the board nose; Trial 2 (Condition #2): looking to the turn buoy; Trial 3 (Condition #3): free during 65 meters at a comfortable speed.

Kinematic Analysis

The paddling motion was documented through a video system employing a digital video camera (Panasonic, DC-FZ 1000II, 50 Hz, Osaka, Japan) mounted on a tripod (Falcon Eyes, FT-120, Hoogeveen, The Netherlands) perpendicular to the course at 20 meters, to capture the entire procedure along the 65-meter length. The camera was positioned perpendicular to the paddling trajectory to minimize parallax error and ensure consistent measurement accuracy.

The various stages of the paddling movement were discerned and identified based on predetermined paddling phases (Freitas et al., 2023; Michael et al., 2009). The pull phase entails fully immersing the blade in the water and swinging it backward to generate forward power (Michael et al., 2009). The exit and recovery phases involve pulling the blade out of the water and returning it to the starting position before the following catch phase (Tsai et al., 2020). A second observer corroborated the event times to ensure precision, enhancing the reliability of measurements associated with the distinct phases executed by the upper limbs.

Following image capture, during the subsequent analysis stage, the Kinovea ® software (version 0.9.5) was used for video editing and conducting kinematic analysis based on sagittal plane images. The selection of the sagittal plane was motivated by its ability to provide a comprehensive view of the paddling motion, considering its kinematic characteristics. Four cycle strokes were analyzed for each subject's left and right sides. The initial six cycle strokes of each trial and the first stroke of each cycle were excluded

to mitigate the impact of the starting acceleration and paddle transfer between sides. The kinematic parameters analyzed in this study included speed, SF, SL, and SI. The speed was derived as distance divided by time, SF (in Hz) as the number of cycles per second, DPS (in m) as the total distance divided by the number of strokes, and SI (in m²/s) as the product of DPS and speed (Abellán-Aynés et al., 2023; Vaquero-Cristóbal et al., 2013).

Surface Electromyography

The assessment of muscle activity was conducted on both sides of the body using a wireless EMG system with built-in accelerometers (Miniwave, Cometa, Milan, Italy; EMGandMotionsTools software 8.7.6.0), probes equipped with a 7-gram memory, and a sampling rate of 2000 Hz at 16 bits. Each subject's skin under the electrodes was shaved, rubbed with sandpaper, and cleaned with alcohol to ensure that the interelectrode resistance did not exceed 5 Kohm (Afsharipour et al., 2019). Transparent bandages with labels (Hydrofilm®, 10 cm x 12.5 cm, USA) were used to cover the electrodes and isolate them from water (Hohmann et al., 2006). The EMG sensors (Kendall™, ECG electrodes, 57x34mm, 57 width mm × 34 length mm, gel area 201 mm², sensor area 80 mm², Dublin, Ohio, USA) were placed following the SENIAM recommendations (Hermens et al., 2000), and the muscles under analysis were the *upper trapezius*, *biceps brachii*, *triceps brachii*, *tibialis anterior*, and *gastrocnemius medialis*, based on their relevance in SUP (Ruess et al., 2013a; Tsai et al., 2020).

Before the paddle assessment, each subject performed three maximal voluntary isometric contractions on dry land for each muscle analyzed to determine the maximum voluntary contraction (MVC). The MVC test is one of the most used methods of EMG signal normalization (Castelein et al., 2015). The contraction was held for 5 seconds with a minimum rest interval of 30 seconds between repetitions, and a minimum 1-minute rest period preceded each new test position. The MVC procedures were conducted with the application of manual resistance by the examiner, according to positioning guidelines of both Surface electromyography for the Non-Invasive Assessment of Muscles (SENIAM) and Noraxon (Scottsdale, AZ, USA) company (Al-Qaisi & Aghazadeh, 2015; Dyson et al., 1996). To ensure isometric conditions, the examiner made every effort to adjust the counterforce appropriately. Participants were positioned in a standing posture for the *upper trapezius* muscle assessment, and the examiner applied a downward force to their shoulders (Konrad, 2005). Regarding the

MVC for the *biceps brachii* and *triceps brachii*, these assessments were carried out with the elbow flexed at approximately 90 degrees, as described in previous studies (Liu et al., 2013; Roman-Liu & Bartuzi, 2018). The examiner provided upper arm stabilization to enhance and standardize activation conditions. For the *biceps brachii*, the forearm was in a supinated position, while a neutral forearm position was maintained for the *triceps brachii*. For the *tibialis anterior*, the foot was held in dorsiflexion, and the toes were not extended, maintaining a neutral position of the foot. For the *gastrocnemius medialis*, the foot was placed in plantar flexion, emphasizing elevating the heel more than pushing the forefoot downward. The force was applied against both the forefoot and the calcaneus to achieve maximum pressure in this position, ensuring a pointed, plantar-flexed foot position. The maximum value of the resulting EMG envelope was determined and averaged across the trials for each test (Boettcher et al., 2008).

During the SUP trials, participants wore custom-made long-sleeved surf suits (Decathlon, Olaian 3/2 mm, Villeneuve-d'Ascq, France) to protect the electrodes and sensors during the trials. During the trials, the EMG measurement was synchronized with a digital video camera (Panasonic, DC-FZ 1000II, Osaka, Japan). Each video was edited according to the trials and then the data was synchronized with the EMG software (EMG and Motion Tools, V8, Cometa, Bareggio Mi, Italy). This study processed synchronization by identifying visible peaks in the accelerometer signal. In this way, it was possible to find the final and initial time of a propulsive phase in the EMG data through the video sequence, with an accuracy of 33.3 ms on a video frame. The pull and recovery phases of the stroke were determined as previously reported elsewhere (Freitas et al., 2023; Michael et al., 2009; Tsai et al., 2020). A second observer checked event times to identify errors. Signal processing started by applying filters to the MVC file. EMG sensors received raw EMG data, and the first frequencies were removed with the following filters: (i) a low pass filter with a cutoff frequency of 400 Hz and Butterworth filter with an order of 4; (ii) a high Pass filter with a cutoff frequency of 20 Hz and Butterworth filter with an order of 4. Each muscle's maximum MVC activation values (μV) were then calculated and presented as percentage MVC (% MVC). The last procedure was to apply the same filters to the signal taken from each trial and the MVC to the trial file. Finally, the mean cycles were exported to an Excel [®] file. The muscular activity was presented for the paddling phases of pull and recovery on the left and right sides.

Statistical Analysis

The normality of data distribution was analyzed with the Shapiro-Wilk test. The mean with standard deviation (SD) was calculated as descriptive statistics. An ANOVA for repeated measures, with sphericity checked using Mauchly's test, was used to identify differences between conditions. The total eta square (η^2) was selected as the effect size index and deemed as: (i) without effect if $0 < \eta^2 < 0.04$; (ii) minimum if $0.04 < \eta^2 < 0.25$; (iii) moderate if $0.25 < \eta^2 < 0.64$ and (iv) strong if $\eta^2 > 0.64$ (Ferguson, 2009). The level of significance was set at $\alpha = 0.05$. If necessary, the Bonferroni post-hoc correction was used to verify significant differences between pairwise ($p < 0.017$), and Cohen's d estimated the standardized effect sizes: (i) trivial if $0 \leq d < 0.20$; (ii) small if $0.20 \leq d < 0.60$; (iii) moderate if $0.60 \leq d < 1.20$; (iv) large if $1.20 \leq d < 2.00$; (v) very large if $2.00 \leq d < 4.00$; (vi) nearly distinct if $d \geq 4.00$ (Hopkins et al., 2009). Statistical analysis was carried out using SPSS statistical software (IBM Corp., Armonk, NY, USA, version 27.0).

Results

Table 1 presents the descriptive and ANOVA data of the variables measured. Condition #3 (free) presented the fastest speed and SF, and highest SI (Table 1). Specifically, the speed ($p < 0.001$, strong effect), SF ($p < 0.001$, moderate effect), and SI ($p < 0.001$, moderate effect) presented significant variance between groups (Table 1). Regarding the muscular activity, during the right pull, the *triceps brachii* ($p < 0.001$, moderate effect), *biceps brachii* ($p < 0.001$, moderate effect), and *tibialis anterior* ($p = 0.003$, moderate effect) on the right side of the body presented significant variance between conditions. Significant variance was also found during the right recovery for the right *upper trapezius* ($p < 0.001$, moderate effect), left and right *triceps brachii* ($p < 0.001$, moderate effects), and right *biceps brachii* ($p < 0.001$, moderate effect). During the left recovery phase, a significant variance was found in the left and right sides of the *upper trapezius* ($p < 0.01$, moderate effect) and *triceps brachii* ($p < 0.01$, moderate effect, and strong effect, respectively).

Table 1. Descriptive statistics (mean \pm SD – standard deviation) of each paddling condition and the one-way ANOVA comparing the three conditions for speed, stroke frequency (SF), stroke length (SL), stroke index (SI) and muscular activity for the muscles analyzed presented as percentage MVC for paddling to the right and left side in the pull and recovery phases of a full stroke cycle, on the right and left sides.

		Condition #1	Condition #2	Condition #3		
		Mean \pm SD	Mean \pm SD	Mean \pm SD	F-ratio (<i>p</i>)	η^2
Speed [m/s] ^a		0.87 \pm 0.18	0.98 \pm 0.23	1.20 \pm 0.21	23.92 (<0.001)	0.65
SF [Hz] ^a		0.52 \pm 0.09	0.54 \pm 0.12	0.65 \pm 0.13	9.57 (<0.001)	0.42
SL [m]		1.69 \pm 0.34	1.85 \pm 0.32	1.86 \pm 0.28	1.60 (0.224)	0.11
SI [m²·s⁻¹]		1.51 \pm 0.56	1.83 \pm 0.64	2.25 \pm 0.67	9.49 (<0.001)	0.42
Right pull [%MVC]						
<i>Upper trapezius</i>	Left	20.15 \pm 9.27	21.79 \pm 7.87	24.35 \pm 8.75	0.84 (0.44)	0.05
	Right	13.23 \pm 7.80	14.56 \pm 6.17	12.28 \pm 6.98	0.37 (0.69)	0.02
<i>Triceps brachii</i>	Left	11.99 \pm 6.34	13.73 \pm 7.23	10.66 \pm 5.10	0.84 (0.44)	0.05
	Right ^b	12.18 \pm 5.58	16.52 \pm 8.45	10.02 \pm 4.50	3.74 (0.03)	0.16
<i>Biceps brachii</i>	Left	9.51 \pm 5.27	9.39 \pm 3.67	7.41 \pm 3.86	1.05 (0.36)	0.05
	Right ^a	6.22 \pm 2.41	6.90 \pm 2.66	8.51 \pm 2.80	2.78 (0.07)	0.13
<i>Tibialis anterior</i>	Left	12.35 \pm 5.96	12.88 \pm 6.28	10.18 \pm 6.36	0.75 (0.48)	0.04
	Right	14.80 \pm 7.39	17.09 \pm 7.73	12.24 \pm 7.70	1.42 (0.25)	0.07
<i>Gastrocnemius medialis</i>	Left	10.90 \pm 5.22	10.53 \pm 4.33	10.98 \pm 4.86	0.04 (0.97)	0.00
	Right	8.04 \pm 4.74	8.81 \pm 4.39	8.45 \pm 4.06	0.11 (0.90)	0.01
Right recovery [%MVC]						
<i>Upper trapezius</i>	Left	17.28 \pm 7.86	19.75 \pm 9.14	14.78 \pm 6.37	4.73 (0.018)	0.07
	Right ^b	14.91 \pm 8.19	17.38 \pm 7.24	10.21 \pm 5.49	15.24 (<0.001)	0.54
<i>Triceps brachii</i>	Left ^{a,b}	19.02 \pm 10.92	21.92 \pm 12.50	33.57 \pm 17.03	17.17 (<0.001)	0.57
	Right ^{a,b}	17.66 \pm 9.41	22.34 \pm 12.22	32.93 \pm 16.06	16.00 (<0.001)	0.55
<i>Biceps brachii</i>	Left ^{a,b}	7.75 \pm 3.40	8.17 \pm 3.39	4.80 \pm 2.17	20.83 (<0.001)	0.62
	Right	8.43 \pm 3.86	9.16 \pm 3.99	8.34 \pm 5.11	0.28 (0.762)	0.02
<i>Tibialis anterior</i>	Left	18.98 \pm 9.25	17.84 \pm 10.41	17.90 \pm 11.76	0.17 (0.842)	0.01
	Right	18.87 \pm 11.36	19.35 \pm 10.11	18.70 \pm 9.73	0.04 (0.963)	0.01
<i>Gastrocnemius medialis</i>	Left	10.88 \pm 4.75	10.66 \pm 4.26	10.43 \pm 4.95	0.15 (0.865)	0.01
	Right	9.43 \pm 4.24	10.03 \pm 5.27	10.73 \pm 6.85	0.50 (0.612)	0.04

Table 1. Descriptive statistics (mean \pm SD – standard deviation) of each paddling condition and the ANOVA comparing the three conditions for speed, stroke frequency (SF), stroke length (SL), stroke index (SI), and muscular activity for the 5 muscles analyzed presented as percentage MVC (% MVC) for paddling to the right and left side in the pull and recovery phases of a full stroke cycle, on the right and left sides. (continued)

		Condition #1	Condition #2	Condition #3	F-ratio (p)	η^2
		Mean \pm SD	Mean \pm SD	Mean \pm SD		
Left pull [%MVC]						
<i>Upper trapezius</i>	Left	11.72 \pm 6.37	12.72 \pm 5.65	10.77 \pm 5.68	1.72 (0.69)	0.12
	Right	26.30 \pm 13.94	26.84 \pm 14.52	27.60 \pm 12.65	0.29 (0.751)	0.02
<i>Triceps brachii</i>	Left	10.21 \pm 6.99	14.55 \pm 9.07	11.35 \pm 6.63	1.74 (0.195)	0.12
	Right	11.08 \pm 7.63	14.30 \pm 5.87	14.10 \pm 6.29	2.58 (0.095)	0.17
<i>Biceps brachii</i>	Left	8.02 \pm 3.04	8.09 \pm 3.43	9.24 \pm 3.20	1.90 (0.170)	0.13
	Right	8.35 \pm 4.81	8.32 \pm 4.20	7.00 \pm 2.68	1.68 (0.206)	0.11
<i>Tibialis anterior</i>	Left	13.50 \pm 5.39	13.91 \pm 7.40	13.56 \pm 7.78	0.03 (0.972)	0.00
	Right	15.04 \pm 9.30	13.21 \pm 6.71	13.14 \pm 7.71	0.54 (0.587)	0.04
<i>Gastrocnemius medialis</i>	Left	9.45 \pm 4.00	10.04 \pm 4.02	9.42 \pm 3.37	0.38 (0.691)	0.03
	Right	10.69 \pm 5.69	11.50 \pm 5.27	10.43 \pm 5.00	0.58 (0.568)	0.04
Left recovery [%MVC]						
<i>Upper trapezius</i>	Left ^b	12.42 \pm 5.82	14.18 \pm 5.20	10.21 \pm 6.15	6.24 (0.006)	0.32
	Right	20.12 \pm 9.57	20.26 \pm 7.68	11.85 \pm 4.91	15.02(<0.001)	0.54
<i>Triceps brachii</i>	Left	21.54 \pm 11.58	25.33 \pm 12.49	29.96 \pm 10.44	6.98 (0.004)	0.35
	Right ^{a,b}	19.17 \pm 10.89	25.56 \pm 13.34	42.25 \pm 18.76	31.84(<0.001)	0.71
<i>Biceps brachii</i>	Left	10.49 \pm 5.14	11.63 \pm 4.86	9.67 \pm 7.82	0.65 (0.528)	0.05
	Right	5.57 \pm 2.80	6.59 \pm 2.32	6.09 \pm 4.32	0.34 (0.71)	0.02
<i>Tibialis anterior</i>	Left	19.38 \pm 9.66	18.90 \pm 12.23	17.67 \pm 11.9	0.33 (0.719)	0.01
	Right	20.19 \pm 13.25	21.68 \pm 13.33	19.59 \pm 9.89	0.32 (0.731)	0.02
<i>Gastrocnemius medialis</i>	Left	10.59 \pm 5.03	10.63 \pm 3.03	12.04 \pm 4.91	1.62 (0.216)	0.11
	Right	9.69 \pm 5.42	10.68 \pm 4.46	10.12 \pm 5.52	0.56 (0.581)	0.04

Condition #1: eyes on the board nose; Condition #2: looking to the turn buoy; Condition #3: free; SF – stroke frequency; SL – stroke length; SI – stroke index; %MVC - percentage of maximum voluntary contraction; η^2 – eta square (effect size index). Superscript *a* – significant differences between conditions #1 and #3. Superscript *b* – significant differences between conditions #2 and #3.

Regarding kinematics, the Bonferroni correction revealed significant differences between conditions #1 and #3 in speed, SF, and SI. Differences were also noted in speed between conditions #2 and #3 in speed (Table 2). As for muscle activity, the greater differences were found in the left recovery for the right *upper trapezius*, with greater activity in condition #2 vs. condition #3, and for the right *triceps brachii* in condition #3 vs. condition #1. Moderate effects were found in the remaining differences obtained, with the exception of the activation of the right *biceps brachii* during the right pull recorded between condition #1 and condition #3. Although the results showed different muscle activity according to each condition, it seems to be clear the

higher activation of *triceps brachii* in the faster condition (condition #3) during recovery phases. During the right pull phase, the *biceps brachii* showed greater activation in condition #3 (vs. condition #1). However, lower activation of *triceps brachii* and *tibialis anterior* was found for the faster condition when compared to condition #2.

Table 2. Pairwise comparison with the Bonferroni post-hoc correction and respective effect size (Cohen's d).

		Condition #1 vs Condition #3			Condition #2 vs Condition #3		
		MD (95CI)	p-value	d [descriptor]	MD (95CI)	p-value	d [descriptor]
Speed [m/s]		-0.33 (-0.43 to 0.23)	<0.001	1.69 [large]	-0.22 (-0.37 to 0.07)	0.005	1.10 [moderate]
SF [Hz]		-0.13 (-0.22 to -0.04)	0.004	1.23 [large]			
SI [m2/s]		-0.74 (-1.09 to -0.38)	<0.001	1.51 [large]			
Right pull [%MVC]							
Triceps brachii	Right				6.49 (1.81 to 11.17)	0.006	0.96 [moderate]
Biceps brachii	Right	-2.28 (-3.65 to -0.91)	0.002	0.27 [small]			
Tibialis anterior	Right				4.85 (1.16 to 8.53)	0.009	0.63 [moderate]
Right recovery [%MVC]							
Upper trapezius	Right				7.16 (4.03 to 10.30)	<0.001	1.11 [moderate]
Triceps brachii	Left	-14.55 (-23.18 to -5.91)	0.001	1.02 [moderate]	-11.65 (-19.86 to -3.45)	0.005	0.78 [moderate]
	Right	-15.27 (-24.63 to -5.92)	0.002	1.16 [moderate]	-10.59 (-17.07 to -4.12)	0.002	0.74 [moderate]
Biceps brachii	Left	2.94 (1.30 to 4.59)	<0.001	1.03 [moderate]	3.37 (1.59 to 5.14)	<0.001	1.18 [moderate]
Left recovery [%MVC]							
Upper trapezius	Left				3.97 (0.96 to 6.98)	0.009	0.70 [moderate]
	Right	8.28 (2.62 to 13.94)	0.004	1.09 [moderate]	8.41 (3.48 to 13.35)	0.001	1.30 [large]
Triceps brachii	Left	-8.42 (-15.03 to -1.80)	0.012	0.76 [moderate]			
	Right	-23.08 (-33.56 to -12.61)	<0.001	1.56 [large]	-16.69 (-23.16 to -10.22)	<0.001	1.06 [moderate]

Condition #1: eyes on the board nose; Condition #2: looking to the turn buoy; Condition #3: free; SF – stroke frequency; %MVC – percentage of maximum voluntary contraction; MD – mean difference; 95CI – 95% confidence intervals.

Discussion

This study compared the kinematics and neuromuscular activity during SUP between three conditions: i) looking at the board nose, ii) looking at the turn buoy, or iii) free. Significant variations were observed in multiple kinematic and EMG parameters between these conditions. The free choice condition resulted in faster speeds, which may be attributed to the higher SF observed and the highest SI, reflecting enhanced stroke efficiency. Additionally, this condition showed greater neuromuscular activity, particularly in the *triceps brachii* during both the left and right recovery phases. During the pull phase, this condition revealed higher activation of the *biceps brachii* (compared with eyes-on-the-board nose condition) and lower activation of the *triceps brachii* and *tibialis anterior* (compared to the looking-at-the-buoy condition), indicating a possible shift in muscle recruitment strategies for improved paddling performance.

The higher activation of the *triceps brachii* during the recovery phase aligns with some previous studies that demonstrated the crucial role of this muscle in paddling motion (Freitas et al., 2023; Tsai et al., 2020). These studies have shown that the *triceps brachii* is activated from the late recovery phase through the intermediate pull phase during SUP. This activation is primarily driven by the arm extension and trunk rotation required in the paddling motion. The extension of the arms and rotation of the trunk inherently lead to increased muscle activation during SUP paddling (Freitas et al., 2023; Tsai et al., 2020). Additionally, Freitas et al. (2023) found that the *triceps brachii* on the opposite side of the stroke typically exhibits higher activation during the pull phase, regardless of paddling direction. This pattern likely reflects the biomechanical demands of stabilizing and driving paddle motion in SUP.

The fixed focus conditions (e.g., looking at the board nose or the turn buoy) were associated with lower kinematic and muscular activity values compared to the free choice condition. This may be due to needing to adjust body positioning and muscular engagement to maintain balance on the board while focusing on a specific point. These adjustments may result in a trade-off, leading to decreased speed and stroke rate but requiring increased stabilization efforts. Hibbert et al. (2023) observed that recreational SUP participants tend to rely more on shoulder muscles for propulsion while using their trunk and hip muscles for stability. This dependence on stabilizing muscles might explain the reduced performance metrics observed in fixed-focus conditions, as practitioners prioritize maintaining balance over achieving speed or power output.

It seems that attentional focus, influenced by different visual fixation points, should be essential for maintaining postural control and balance stability. Schram et al. (2016a) stated that balance during SUP is significantly affected by vision, with greater postural sway observed when visual input is restricted. These findings correspond with improved performance metrics in conditions that allow for natural and dynamic visual environments. In addition, Wulf et al. (2010) and Marchant et al. (2008) showed that an external focus of attention can enhance neuromuscular coordination and efficiency, leading to better performance outcomes. For instance, Marchant et al. (2008) discovered that athletes who focused on external targets, such as the bar during a lift, showed reduced *biceps brachii* activity and improved neuromuscular coordination. Similarly, Pesce et al. (2007) demonstrated that athletes with superior visual adjustment skills performed better in tasks requiring dynamic focus shifts, further supporting the benefits of free visual focus. These findings reinforce our results, indicating that allowing a free visual focus can significantly enhance performance metrics, such as speed and muscle activation, in SUP.

The current study suggests that having the freedom to adjust head positioning allows for more natural paddling mechanics, potentially leading to improved stroke efficiency, as indicated by the significantly higher SI observed in the free choice condition. These higher SI values demonstrate the ability to improve the effectiveness of each stroke rather than relying solely on increased SF for faster speeds. Additionally, the results consistently showed higher *triceps brachii* activation in the faster condition during the recovery phases, emphasizing the importance of this muscle in repositioning the paddle efficiently for the next stroke. During the pull phase, the higher activation of the *biceps brachii* (compared to the eyes-on-the-board nose condition) and lower activation of the *triceps brachii* and *tibialis anterior* (compared to the looking-at-the-buoy condition) further underscore the efficient neuromuscular strategies adopted in the free choice condition. This change in muscle recruitment strategies indicates a more efficient distribution of work among muscle groups. It reduces unnecessary strain on stabilizing muscles, such as the *tibialis anterior*, while enhancing pulling force. Together, these findings emphasize that improved kinematics (i.e., SF and SI), optimized muscle activation during recovery phases, and strategic shifts in muscle recruitment during the pull phase are likely key contributors to enhanced paddling performance in the free choice condition

While this study provides valuable insights into the effects of attentional focus on SUP performance, some limitations should be considered. Cross-sectional design limits the ability to establish causal relationships between attentional focus and performance

metrics. Future studies with longitudinal designs could help determine long-term effects. The paddling intensity was self-selected, but heart rate monitoring confirmed consistent effort levels across conditions. Nonetheless, including additional physiological markers could further refine intensity control. Additionally, the sample size and the training level (recreational SUP practitioners) may limit the generalizability of these findings. Expanding the sample to include different experience levels and genders and exploring performance differences under maximal effort conditions would provide a more comprehensive understanding of attentional focus influences on SUP performance.

These findings can potentially influence the development of more effective and targeted training programs and provide valuable insights for improving competitive and recreational performance in SUP. Encouraging paddlers to have a free attentional focus during training can enhance SF, muscle engagement, and overall paddling efficiency. Moreover, the results suggest that SUP training protocols should incorporate different vision fixation strategies to optimize stroke length, paddling speed, and neuromuscular coordination under those conditions. Training under fixed-focus conditions, such as when navigating buoys in races, is crucial for preparing athletes to adapt to varied competitive environments. This dual approach ensures that athletes can balance performance consistency and adaptability across different race conditions. Future studies should examine the causal relationships between attentional focus, neuromuscular activity, and kinematics while also exploring how these findings apply to athletes of various expertise levels and in different environmental contexts.

Conclusion

Different attentional focus strategies, influenced by various visual focus conditions during SUP, can significantly affect kinematic performance and neuromuscular activation. The condition allowing paddlers to direct their looks freely resulted in the highest speeds, SI, and SF, indicating improved overall performance. Additionally, this free choice condition showed greater neuromuscular activity, particularly in the *triceps brachii* during both the left and right recovery phases, emphasizing the critical role of this muscle in paddle repositioning. During the pull phase, the faster condition revealed higher activation of the *biceps brachii* and lower activation of the *triceps brachii* and *tibialis anterior*, perhaps reflecting more efficient muscle recruitment strategies. These findings suggest that a natural and unrestricted attentional focus enables paddlers to adopt more efficient paddling mechanics, likely due to enhanced neuromuscular coordination and reduced unnecessary muscle strain.

Chapter 4. General Discussion

The growing popularity of SUP has led to an increased interest in understanding the factors that influence performance in this sport. This thesis aimed to analyze kinematic and neuromuscular factors that influence SUP performance in real-life contexts, in recreational level athletes. In this sense, it comprises four studies that investigate different biomechanical and neuromuscular aspects of SUP performance. By employing systematic analysis and cluster modeling, these studies provide insights into muscle activation patterns, kinematic variables, and the effects of visual focus conditions. To achieve that purpose, a sequence of studies was developed with the following specific aims:

- Study 1 identified and summarized the findings reported in the literature regarding the performance analysis in SUP under different test conditions and experience levels.
- Study 2 aimed to analyze the muscle activity during the stroke cycle, considering the paddling side, comparing the opposite and adjacent muscles to the paddle stroke, and examining activation in the upper and lower limbs, to better understand muscle activation patterns during paddling.
- Study 3 was conducted to classify SUP practitioners using cluster analysis of kinematic and neuromuscular activity parameters to differentiate performance levels.
- Study 4 aimed to analyze the kinematics and muscle activity in SUP under different external focus, specifically, comparing three conditions: i) looking at the board nose, ii) looking at the turn buoy, or iii) free.

The first study, a systematic review, compiled data from 21 studies involving 238 participants, covering anthropometry, biomechanics, physiology, and equipment assessment. It highlighted that elite Stand-Up Paddleboarding (SUP) athletes generally have higher muscle mass and lower body fat percentages, utilizing more efficient paddling techniques crucial for performance optimization and injury prevention (Schram et al., 2014). The lower body fat in elite athletes may be due to specific preparation for races that reduce body fat during the competition period (Burgess & Bommarito, 2019). However, experienced SUP practitioners show diversity in body composition influenced by fitness level, experience, gender, age, and individual characteristics (Schram et al., 2014, 2016a, b).

Biomechanical analyses have focused on stroke parameters, muscle activation, and balance to reveal differences between experienced and novice paddlers. According to

Schram et al. (2019), experienced paddlers demonstrate more efficient stroke mechanics with greater shoulder and elbow extension. Additionally, stand-up paddleboard (SUP) training has been found to improve balance stability, particularly in older adults, leading to reduced trunk sway in challenging postures (Schram et al., 2016c). Stroke parameters such as distance covered, speed and paddle rate are also considered crucial metrics (Schram et al., 2016c, 2017a; Balikian et al., 2022; Neiva et al., 2020). In competitive events, participants covered an average distance of 13.56 km during a marathon race (Schram et al., 2017a). Furthermore, in calm water field tests, distances covered in 30 minutes ranged from 3,700 m to $4,173.8 \pm 241.8$ m (Balikian et al., 2022; Neiva et al., 2020). Moreover, maximal speeds during SUP testing were reported as 2.19 ± 0.32 m/s in calm water (Neiva et al., 2020), 2.18 ± 0.16 m/s for elite athletes, 1.93 ± 0.24 m/s for recreational athletes, and 1.50 ± 0.15 m/s for sedentary individuals on an ergometer (Schram et al., 2016a). It was also noted that field speeds (3.09 ± 0.32 m/s) were higher compared to laboratory speeds (2.17 ± 0.13 m/s) (Schram et al., 2016b). Paddle rate and length also varied among different groups. Elite athletes exhibited a maximum paddle rate of 69.6 paddles/min and a mean paddle length of 2.19 meters, in contrast to 55.47 paddles/min and 2.24 meters for recreational athletes, and 42.27 paddles/min and 2.34 meters for sedentary individuals (Schram et al., 2016a).

Physiologically, SUP is demanding, involving significant cardiovascular and anaerobic activity. Training enhances both aerobic and anaerobic capacities (Schram et al., 2016c). Elite athletes show higher anaerobic power outputs and VO_{2max} compared to recreational paddlers, reflecting improvements in fitness due to training (Schram et al., 2016c, 2017b). Furthermore, heart rate (HR) is a key indicator of exercise intensity, with SUP sessions often involving HRs above 70% of maximum, particularly during intense activities like paddling back out after falling off the board.

Innovations in SUP equipment is crucial for enhancing performance and accessibility. Equipment, such as boards and paddles, significantly impacts performance, with high-tech materials offering advantages in speed and stability. Studies highlight the differences in performance between in-water and out-of-water strokes, particularly in force production and gear ratios (Lamb, 1989; Kleshnev, 2005). Field evaluations of SUP boards, paddles, and fins demonstrate that high-tech equipment performs better in terms of paddle speed and stability (Novak, 2021). Customizable fin designs using 3D printing show promise for further performance improvements (Novak, 2021). Additionally, the stability of the human-SUP system is heavily influenced by the rider's position on board, with a central position providing the greatest stability. This aspect is

critical for both performance and safety during races, also analyzing race behavior has shown changes in participation and performance over different events, reflecting the ongoing evolution of the sport and its equipment (Dyer, 2021)

In this review, it was clear that research underscores the diversity in anthropometric, biomechanical, and physiological characteristics of SUP practitioners. Several key points were derived through a critical analysis of the literature for external and internal parameters commonly used to evaluate SUP performance, which can be enumerated as follows: i) the importance of proper muscle recruitment and coordination, involving predominantly the upper limbs, it also significantly activates the trunk, hip stabilizers, and knee stabilizers (Ruess et al., 2013; Tsai et al., 2020); ii) discrepancies in performance metrics such as distance covered, stroke rates, and muscle activation patterns during SUP highlight the need for comprehensive interpretation of results (Schram et al., 2016c; Neiva et al., 2020); iii) the participants position in the SUP board showed to affect muscle activation and the visual focus can play a critical role in maintaining balance and stability during SUP (Wulf, 2007; Schram et al., 2016a; Stoate & Wulf, 2011). Therefore, taking into account these three premises, the focus of the subsequent experimental studies was: i) analyze the muscle activity during the stroke cycle, considering the paddling side, comparing the opposite and adjacent muscles to the paddle stroke, and examining activation in the upper and lower limbs; ii) classify SUP practitioners using cluster analysis of kinematic and neuromuscular activity parameters to differentiate performance levels; iii) understand the relationship between the muscular activity and the kinematical parameters with the alteration of different visual focus point.

Analyzing the movement patterns, the results of the second study showed that SUP participants spent more time in the recovery phase (60%) compared to the pull phase (39%). Moreover, higher muscle activation levels were observed in the *upper trapezius*, *triceps brachii*, and *tibialis anterior* muscles. Nevertheless, significant differences were found in muscle activation patterns between the paddling sides. Higher activation was observed on the opposite side of the paddle stroke, particularly in the *upper trapezius* and *biceps brachii* during the recovery phase. This finding aligns with previous research by Tsai et al. (2020), which highlighted the role of the upper trapezius in stabilizing the shoulder during SUP paddling. The differential muscle activation suggests that targeted training can improve muscle balance and reduce the risk of injury, a point corroborated by Ruess et al. (2013), who emphasized the importance of balanced muscle activation in preventing overuse injuries in paddle sports. The role of the *upper trapezius* in SUP has been documented in various studies. For instance,

Ruess et al. (2013) found that the *upper trapezius* is crucial for maintaining shoulder stability during dynamic movements. This is particularly important in SUP, where the repetitive motion of paddling can lead to muscle imbalances and potential injuries. By identifying specific muscle activation patterns, this study provides a basis for developing targeted training programs that address these imbalances.

Our study also emphasizes the role of the lower limbs as stabilizers during the pull phase, while the upper limbs function as propulsors. This indicates that the lower limbs are more activated during the pull phase to stabilize the board and support upper limb movement. Significant differences were observed in muscle activation between the pull and recovery phases, particularly in the *tibialis anterior* muscle on the opposite side of the paddling stroke. This could suggest a compensatory mechanism to manage the board's instability by the practitioners. Alternating paddling sides can help maintain muscle balance and reduce fatigue. These insights can be integrated into SUP training programs, switching movements between stroke sides to promote balanced muscle recruitment and reduce fatigue. Incorporating these recommendations can enhance overall paddling performance and minimize injury risk.

The cluster analysis allowed us to classify SUP practitioners based on performance, distinguishing between faster, medium, and slower performers. When we try to understand more about biomechanical factors that influence SUP performance, the results showed that faster performers demonstrated higher activation of the *triceps brachii* and greater stroke frequencies, indicating these variables as key performance differentiators. This finding supports the work of Schram et al. (2019), who found that experienced paddlers exhibit more efficient stroke mechanics and higher muscle activation levels.

Indeed, different neuromuscular activations during the pull and recovery phases. The faster performers showed higher myoelectric signaling for the left *triceps brachii* during the right pull. Moreover, they also showed higher myoelectric signaling during the right recovery phase of the stroke for the left *triceps brachii* (i.e., compared with poor performers). It has been noted that the muscles on the opposite side of a stroke show more activity than the adjacent muscles throughout the paddling cycle (Freitas et al., 2023). In addition, Tsai et al. (2020) have suggested that the *triceps brachii* muscle is primarily activated from the later stage of the recovery phase to the middle stage of the pull phase, as a result of the straightening of the arms and torso twisting. This could explain the increased activation of the *triceps* during the pull and recovery phases.

Based on the current findings, it seems that higher stroke frequency and neuromuscular activation are more prominent in faster performances.

Determinant factors varied with speed, highlighting the importance of specific muscle activations. Key findings indicated that faster performers exhibited higher myoelectric signaling in the *triceps brachii* during both the pull and recovery phases. This contrasts with slower performers, who showed low activations in the *biceps brachii* and *upper trapezius* during the pull phase. The importance of muscle activation during the recovery phase was emphasized, as it occupies a significant portion of the stroke cycle. The identification of key performance differentiators through cluster analysis is a significant contribution to the literature. These findings underscore the importance of muscle activation throughout the stroke cycle and guide for improving SUP performance through targeted training and technique optimization, focusing on the recovery phase and in the work of the muscles involved during this phase of the stroke. The importance of the recovery phase in paddle sports has been highlighted before. For instance, Hibbert et al. (2023) found that efficient muscle function during the recovery phase is critical for maintaining endurance and preventing fatigue. By identifying specific muscle groups that are crucial during this phase, these results provide valuable insights for developing training programs that enhance recovery efficiency and overall performance.

In sports like SUP, where balance is constantly challenged by water conditions, understanding how visual focus affects neuromuscular activation and kinematics can be important. This way, the last study compared kinematics and neuromuscular activity during SUP under three conditions: looking at the board nose, looking at the turn buoy, and free visual focus. The results showed significant variations in kinematic and neuromuscular activity between these conditions. Nevertheless, the free choice condition, where participants chose their natural visual focus, led to faster speeds and higher stroke frequencies, along with greater neuromuscular activity, especially in the right *triceps brachii* during the recovery phases. A free visual focus condition allows for better performance metrics, likely due to enhanced neuromuscular coordination and reduced unnecessary muscle strain (Schram et al., 2016a).

The key findings of the study highlighted the impact of visual focus on performance. These suggest that allowing paddlers to use their preferred visual strategy can enhance performance by optimizing neuromuscular coordination. The study's findings are consistent with research by Woollacott and Shumway-Cook (2002), which showed that visual input is crucial for maintaining balance and stability in dynamic activities. This

condition also showed increased neuromuscular activity, particularly in the *triceps brachii*, supporting previous findings that underscores the importance of this muscle in paddling motion (Tsai et al., 2020). Moreover, the higher *triceps brachii* activation during the recovery phase was aligned with literature that showed this muscle's significant role from the late recovery phase to the intermediate pull phase (Tsai et al., 2020).

The study also found that conditions with a fixed focal point, such as looking at the board nose or a turn buoy, showed lower kinematic and muscular activity values. This could be because when practitioners are instructed to focus on a specific point, it may lead to adjustments in body position and muscular participation to reduce instability on the paddle board, potentially impacting speed and stroke rate to maintain stability. Additionally, previous results suggested that instructions to focus externally on a point (such as a bar) resulted in lower activity in the *biceps brachii* muscle compared to instructions to focus internally on the arms or no specific focus at all. This implies that an external focus of attention enhances neuromuscular coordination (Marchant et al., 2008). The study suggests that the freedom to choose a vision focus allows for more natural and efficient paddling mechanics, which leads to improved performance. This freedom likely enables paddlers to adopt more efficient movement patterns, reducing unnecessary muscle strain and allowing for better overall performance with higher stroke frequencies.

The implications of this study extend to the development of SUP training programs. It emphasizes the importance of incorporating both free visual focus and fixed focal point training to help athletes adapt to different race conditions and maintain performance across varying scenarios. Understanding whether the increased freedom in visual focus leads to higher stroke frequency and greater muscle activation or if greater muscle recruitment allows for higher stroke frequency is critical. This study suggests a potential cause-effect relationship where the freedom in vision allows for more natural and efficient paddling mechanics, leading to increased performance. This freedom likely enables paddlers to adopt more efficient movement patterns, reducing unnecessary muscle strain and allowing for higher stroke frequencies and better performance.

The integration of findings from these four studies provides a holistic understanding of SUP performance. The consistent identification of muscle activation patterns and stroke mechanics as critical determinants underscores the multifaceted nature of SUP performance. By employing diverse methodologies, including EMG analysis, and

kinematic assessment, this thesis offers a comprehensive framework for evaluating and enhancing SUP performance. Nevertheless, some main limitations of this thesis should be addressed:

- The studies primarily involved recreational paddleboarders, right-handed and males, which may not fully represent the experiences and performance characteristics of more experienced or elite SUP athletes.
- Although the major muscle groups were analyzed, we must acknowledge that surface electromyography provides information only about these muscles.
- The trials were performed at submaximal effort and maximal effort is required for further understanding of the influencing factors of SUP performance.
- We should understand that ecological context can impact SUP performance and that external variables such as water conditions and weather, although monitored, can potentially influence experimental procedures.

Chapter 5. Overall Conclusions

The current thesis focused on various biomechanical variables crucial for understanding SUP performance. Specifically, we examined speed, stroke frequency, stroke length, stroke index, and electromyographic signal of major muscles involved in SUP to provide a comprehensive analysis of how these factors contribute to performance. Our findings highlighted the importance of specific muscle activity throughout the stroke cycle and provided direction for improving SUP performance. Regarding the specific purposes, the conclusions of the present thesis were:

- i) SUP athletes generally exhibit higher muscle mass and lower body fat percentages, which are correlated with more efficient paddling techniques.
- ii) There is a lack of research in SUP, specifically understanding the determinants of performance, although several studies have highlighted the diversity in anthropometric, biomechanical, and physiological characteristics of SUP practitioners.
- iii) SUP athletes of the recreational level spent more time in the recovery phase than in the pull phase during the paddling stroke.
- iv) During the SUP stroke cycle, muscles on the opposite side of the paddling arm showed higher activation levels compared to adjacent muscles. This highlights the importance of alternating paddling sides to maintain muscle balance and reduce fatigue.
- v) Different muscle activation patterns were found between the pull and recovery phases of the stroke, emphasizing the need for specific training interventions to enhance muscle coordination and efficiency during these distinct phases
- vi) The cluster analysis revealed that faster participants demonstrated higher stroke frequencies and distinct neuromuscular activation patterns, particularly higher triceps brachii activity during the recovery phase. This differentiation is crucial for developing targeted training programs aimed at improving performance
- vii) Different visual focus conditions significantly impact SUP performance, with the free choice condition resulting in the highest speeds, stroke frequencies, and muscle activation levels (i.e., right *triceps brachii*). This indicates that allowing athletes to choose their visual focus may optimize performance.

Chapter 6. Suggestions for future research

The results obtained in the thesis represent an initial step towards gaining a deeper understanding of the kinematic and neuromuscular factors that impact SUP performance in real-world settings. The findings emphasize the importance of balanced muscle activation, efficient stroke mechanics, and optimal visual focus for enhancing performance. This thesis consolidates insights from four studies to present a comprehensive framework for comprehending and improving SUP performance. However, further research is necessary to fully understand the diverse factors influencing SUP performance. Hence, several recommendations for future research can be suggested, including:

- i) Replicate previous studies but include a more diverse sample, with different experience levels and genders to provide more generalizable results.
- ii) Reproduce similar studies but differ the distances, intensities, and contexts, comparing genders and different levels of experience. It would also be relevant to analyze the existence of inter-individual and intra-individual differences in neuromuscular and kinematic parameters.
- iii) Understand the neuromuscular and kinematic response to different SUP techniques (i.e., using different hand placement positions when gripping the paddle) or fatigue situations. Analyzing the effects of neuromuscular fatigue on the kinematics of SUP practitioners is essential.
- iv) Integrating more advanced technologies such as motion capture systems and force sensors could enhance the understanding of SUP kinematics and kinetics. Future research should leverage these technologies for more precise and comprehensive data.
- v) Analyze the relationship between propulsive force (kinetic) and the pattern of neuromuscular activation (EMG) throughout the paddling cycle in SUP practitioners, as well as relate the implications of force applied in paddling with linear kinematic variables associated with board propulsion.
- vi) Exploring the effects that can help coaches optimize the rowing techniques of practitioners and athletes, as well as support researchers to expand knowledge in this area of research, is crucial. It is essential throughout the process to publish the studies and share them with the scientific community.

Chapter 7. References

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