INTERNATIONAL JOURNAL OF
SPORTS PHYSIOLOGY
AND PERFORMANCE

Which strength manifestation is more related to regional swimmers' performance and in-water forces? Maximal neuromuscular capacities vs. maximal mechanical maintenance capacity

Journal:	*International Journal of Sports Physiology and Performance*
Manuscript ID	IJSPP.2023-0475.R2
Manuscript Type:	Original Investigation
Date Submitted by the Author:	25-Feb-2024
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Keywords:	dry-land exercises, linear position transducer, load-velocity relationship, velocity-based training, sprint

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Abstract

Purpose: To explore the association of the load-velocity (L-V) relationship variables and ability to maintain maximal mechanical performance during the prone bench pull (PBP) exercise with sprint swimming performance and in-water forces. **Methods**: Eleven competitive adult male swimmers (50-m front crawl World Aquatics points: 488 ± 66, performance level 4) performed one experimental session. The L-V relationship variables (L_0 [*i.e.,* maximal theorical load at zero velocity]; v_0 [i.e., maximal theorical velocity at zero load] and, A_{line} [*i.e.,* area under the L-V relationship]) and maximal mechanical maintenance capacity were assessed at the beginning of the session. Afterwards, sprint swimming performance and in-water forces production were tested through a 50-m front crawl all-out trial and 15-s fully-tethered swimming, respectively. **Results**: Only v_0 presented high positive associations with 50-m time and swimming kinematics ($r \geq 0.532$; $p \leq 0.046$). The L_0, v_0 and A_{line} showed very high positive associations with the in-water forces during tethered swimming ($r \geq 0.523$; $p \leq 0.049$). However, the ability to maintain maximal mechanical performance, assessed by the mean velocity decline during the PBP, was only significant correlated with stroke rate ($r = -0.647$; $p = 0.016$) and stroke index ($r = 0.614$; $p = 0.022$). **Conclusions**: These findings indicate that maximal neuromuscular capacities, especially v_0, have a stronger correlation with swimming performance and in-water force production than the ability to maintain maximal mechanical performance in level 4 swimmers.

Key Words: dry-land exercises; linear position transducer; load-velocity relationship; velocity-based training; sprint

Introduction

Swimmers' propulsive force production is one of the most determinant factors in swimming performance.[1] However, to date, no methodology has been able to measure it precisely due to different limitations (*e.g.,* lack of displacement during tethered swimming). Yet, it is established that its magnitude depends on the ability to effectively apply force in the water[2,3] and the inherent maximal neuromuscular capacities.[4,5] To approach this challenge, methodologies such as tethered swimming have been employed to estimate the interaction between these two factors. Moreover, it is important to discern between these aspects,[2,6] from a practical standpoint, the swimmers' ability to apply force is developed during swimming sessions whereas maximal neuromuscular capacities are mostly enhanced through specific dry-land resistance training programs.[2,6,7] Despite the amount of research on this topic, the specific effects of dry-land resistance training programs on swimming performance vary considerably.[7]

As most propulsive forces are produced by the upper limbs, many of the dry-land exercises are focused on the development of upper-body force and power capabilities.[6] For instance, the lat pull-down and pull-ups are two of the most used exercises because overload one of the main muscles activated during swimming, the latissimus dorsi.[8] Concretely, the lat pull-down one repetition maximum (1RM) and the body velocity displacement during the pull-up exercise were significantly correlated with swimming performance.[9,10] On the other hand, the prone bench pull (PBP) stands out as another key exercise for stimulating the latissimus dorsi, which has been less explored in swimming scientific literature. Unlike the pull-up and lat pull-down, the PBP is executed in the horizontal plane and although this might slightly deviate from the direct mechanics of swimming motion, it offers a potentially complementary perspective for the comprehensive development and assessment of swimmers. First, the PBP allows to evaluate the full force spectrum from very high (*i.e.,* barbell weight) to very low velocities (*i.e.,* heavy loads). Second, it uses may also rely on its low-cost and easy implementation (*i.e.,* compared to expensive lat pull-down machines). Third, the lifting does not involve the body weight and this is an important characteristic as adolescents' swimmers struggle to perform loaded or even the free lat pull-down exercise.

Low-volume with high-force/velocity resistance training programs are recommended for optimal transfer to sprint swimming performance[9] as swimmers need to apply high amounts of forces in a relatively short period of time (*i.e.,* high stroke rate).[7] In this sense, the velocity-based training (*i.e.,* resistance training method that prescribe the intensity and volume based of the lifting velocity; VBT) may provide useful and objective information about the assessment and prescription of dry-land resistance training programs.[11] One recent VBT application consists of estimating the maximal neuromuscular capacities through the load-velocity (L-V) relationship (*i.e.,* individual velocity data obtained against several external loads).[12–14] Specifically, the variables obtained by these individual L-V relationships are indicators of maximal force (*i.e.,* maximum theorical load at zero velocity; L_0), maximum velocity (*i.e.,* maximal theorical velocity at zero load; v_0) and maximum power (*i.e.,* area under the L-V relationship line; A_{line}).[14] The main advantage of this approach compared to the traditional force-velocity relationships is that the distance from the first experimental point to v_0 is reduced, allowing a higher reliability of the parameters.[12,14] However, to date, no previous study has explored whether the L-V variables obtained from dry-land exercises are related to the sprint swimming performance and in-water forces. This type of research would allow to elucidate which exercises and strength manifestations are more important to target through resistance training programs in order to enhance sprint swimming performance.

Identifying the key strength qualities related to sprint swimming performance should be mandatory when prescribing the dry-land resistance training programs.[15,16] In this regard, VBT not only allows to estimate the maximal neuromuscular capacities but also, the ability to maintain high velocity outputs within a set. Specifically, two variables have been proposed to explore the ability to maintain mechanical performance using velocity monitoring: mean velocity maintenance (*i.e.,* overall capacity to maintain the maximum velocity performance; MVM) and mean velocity decline (*i.e.,* degree of muscular fatigue experienced at the end of the set; MVD).[17] Both variables allow to assess how the velocity loss pattern is different between individuals without the need to performed sets to failure which may cause a technical alteration during the subsequent swimming training session.[18] Despite the usefulness of these variables to assess the ability to maintain mechanical performance, no previous research has studied its association with the degree of muscular fatigue experienced during sprint swimming.

Therefore, the present research aimed to examine the association of the maximal neuromuscular capacities derived from the L-V relationship (L_0, $v_{0,}$ and A_{line}) and the ability to maintain mechanical performance (MVD and MVM) during the PBP exercise with sprint swimming performance and in-water forces variables. It was hypothesized that all L-V relationship variables as well as the ability to maintain high mechanical outputs would be associated with 50-m sprint swimming performance and kinematics as well as in-water forces variables measured by tethered swimming.[10,13,17]

Methods

Subjects

Eleven competitive adult male swimmers (21.9 ± 3.8 years, 171.0 ± 33.1 cm of body height, 85.6 ± 30.2 kg of body mass, and 50-m front crawl World Aquatics points: 488 ± 66, performance level 4) volunteered to participate in the current study.[19] Swimmers were required to have at least 5 years of regional-national competitive and strength training experience. Furthermore, swimmers with an attendance percentage below 85% or with an injured in the last 6 months were excluded. All the swimmers trained six swimming and four dryland sessions per week in the same squad and under the direction of the same coach, with a weekly training volume of 37.36 ± 5.35 km (mean ± standard deviation). The protocol was fully explained to the participants before providing written consent to participate. The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki), and the protocol was approved by the University Ethics Committee (approval no: 2046/CEIH/2021).

Design

A cross-sectional study design was conducted in two sessions (preliminary and experimental sessions) to eliminate any residual fatigue effect. Swimmers were familiarized with the tests prior to the study onset (supplementary file 1). Swimmers were assessed a week after their main season competition (*i.e.,* peak performance), being the first evaluation session separated by 24 hours of rest from a light-moderate in-water training session. The second evaluation session was conducted the day after, at the same time of the day to avoid systematic bias due to circadian variation.[20] In addition, swimmers were instructed to maintain their normal dietary patterns as well as to refrain from performing other vigorous exercise 24 hours before each testing session. Swimmers were verbally encouraged during all the land and in-water tests.

Methodology

Preliminary Session (Session 1)

The first goal of the preliminary session was to estimate the 1RM during the Smith machine PBP exercise. A general warm-up was performed, consisting of jogging, dynamic stretching, and upper-body joint mobilization exercises followed by a specific warm-up consisting of three sets of five repetitions against 17 (barbell mass), 30 and 40 kg. Afterwards, a standard incremental loading protocol was performed starting by an external load set at 40 kg and progressively increased in steps of 10 kg until the MV (*i.e.,* average velocity from the first positive velocity until the velocity is 0 m/s) was lower than 0.60 m/s. Three repetitions were performed with light loads (MV > 1.00 m/s), two repetitions with moderate loads (MV from 1.00 to 0.80 m/s) and only one repetition with heavy loads (MV < 0.80 m/s).[13,21] Rest periods were set to three minutes for light-to-moderate loads and five minutes for heavy loads. Subjects received auditory MV feedback immediately after completing each repetition to maximize the accuracy of 1RM prediction.[22] Finally, the 1RM was estimated from the individual L-V relationships using a minimal velocity threshold of 0.48 m/s.[23]

After the PBP 1RM was estimated, subjects performed two sets of 10 repetitions separated by four minutes of rest. The first set was performed against the 70%1RM and the second set against an external load of 60 kg. The 70%1RM was selected as it is a relative load commonly used by swimmers in their dry-land resistance training programs,[7] while the same absolute load of 60 kg was used to compare subjects under the same loading conditions. The PBP technique required participants to lie face down, with their arms fully straightened and gripping the barbell at a self-selected width. The range of movement were maintained constant on each repetition using the telescopic supports of the Smith machine. The repetition was deemed invalid when barbell failed to touch the bottom of the bench. The calves of the legs were secured to avoid the legs movements and facilitate the force application.[13]

Experimental Session (Session 2)

The experimental session started with the same general warm-up described during the preliminary session. The specific warm-up comprised one set of 10, five and two repetitions against the 60%1RM, 70%1RM, and 80%1RM, respectively.[13] Afterwards, subjects rested for three minutes and then they performed the PBP exercise at maximal intended velocity against five loads in the following order: three repetitions with the lightest load (17 kg; L1), two repetitions with the heaviest load (85%1RM; L5 = 78.8 ± 9.7 kg), and two repetitions with three intermediate loads spread equitably between L1 and L5 (L2 = 32.1 ± 2.6 kg; L3 = 47.4 ± 5.0 kg; L4 = 62.7 ± 7.7 kg). Five minutes after completing the loading test, subjects performed one set of 10 repetitions against the 70%1RM (65.1 ± 7.6 kg) and another set against the same absolute load of 60 kg (65.3 ± 7.9%1RM) separated by four minutes of rest. Subjects received auditory MV feedback immediately after completing each repetition to maximize mechanical performance.[24]

After 30 minutes of resting, swimmers headed to a 25-m swimming pool (25-m length × 16.5-m width with 27.2 °C water temperature, 29.55 °C air temperature, and 52% of humidity) and performed a standardized warm-up of 1000-m consisting of 400-m swim, 100-m pull, 100-m kick, 4 × 50-m at increasing speed, and 200-m easy swim.[25]

Swimmers then rested for 10 minutes and performed a 50-m front crawl all-out trial with in-water start. After the completion of the 50-m all-out trial swimmers rested 15 minutes and performed 15 seconds fully-tethered swimming. The start and end of the 15 seconds were determined through an auditory signal. Before that, swimmers swam for 5 seconds at low intensity, to avoid any inertial effect.[6] Although all the participants were familiar with tethered swimming, they underwent a familiarization protocol with all the procedures before testing.[26]

Measurement Equipment and Data Analyses

Body height (Seca 202 Stadiometer, Seca Ltd., Hamburg, Germany) and body mass (Tanita BC 418 segmental, Tokyo, Japan) were measured at the beginning of the preliminary session. A validated linear position transducer (GymAware RS, Kinetic Performance Technologies, Canberra, Australia) was vertically mounted to the Smith machine's barbell and provided the MV from all repetitions while the data was immediately provided via Bluetooth to a tablet (iPad, Apple Inc.) using the GymAware v2.4.1 app.[27] The L-V relationships were modelled by a linear regression model considering two different approaches: multiple-point method (*i.e.,* using data points acquired from the five different loads [L1-L5-L2-L3-L4]) and two-point method (*i.e.,* using data points acquired from only two distant loads [L1-L5]).[13,21] Specifically, a least-square linear regression model $L(MV) = L_0 - slope \times MV$ was constructed individually to estimate the L-V relationship variables: L_0 (*i.e.,* theorical load at 0 m/s), v_0 (*i.e.,* $v_0 = L_0 / slope$) and A_{line} (*i.e.,* $A_{line} = L_0 \times v_0 / 2$). Only the repetition with the highest MV of each load was considered for modelling these relationships.[13,21] The MVD and MVM were calculated considering the MV data collected during the set of 10 repetitions performed against the 70%1RM and 60 kg. Specifically, the MVD was computed as follows: $\mathrm{MVD} = [(\mathrm{MV}_{\mathrm{last}} - \mathrm{MV}_{\mathrm{fastest}}) / \mathrm{MV}_{\mathrm{fastest}}] \times 100$, while the MVM was calculated as $\mathrm{MVM} = 100 - [(\text{mean set velocity} \times 100) / \mathrm{MV}_{\mathrm{fastest}}]$[17] (supplementary file 2).

The 50-m front crawl trial was recorded with a Sony FDR-AX53 (Sony Electronics Inc) at 100 Hz sampling rate. The camera was positioned in the stands of the pool, at a water height of ~7 m, and at a distance of ~20 m from the swimmer. The camera recorded by following the swimmer with an optical zoom that captured an area of 7 m, with the swimmer maintain in the center of the image. Videos were analyzed by one expert evaluator on an in-house customized software for race analysis in competitive swimming.[28] Clean swimming speed, stroke rate, stroke length, and stroke index were the swimming kinematic variables collected as previous literature.[29,30] The intraclass correlation coefficient was computed to verify the absolute agreement between repeated measures for each trial of the sole evaluator, with a very-high agreement (intraclass correlation coefficient: 0.977– 0.999).

During tethered swimming a steel cable was attached to swimmers' hip through a floating trapezoidal structure and fixed to a load cell (RSCC S-Type, HBM) with an angle of 10° with the water surface. The recording sample was set at 1500 Hz. Then, analog data were converted (celula version 1.4, Remberg, Force Isoflex), registered, and exported (NIUSB600, National Instruments) to a specific software (myoRESEARCH, Noraxon). The force–time curves were processed, with the angle correction,[31] using a fourth-order Butterworth low- pass digital filter (4.5 Hz cut-off frequency). From the force–time curves, the following parameters were computed as previously shown:[10,32] average force (F_{avg}), mean of force values recorded during the 15 seconds; maximum force (F_{max}), highest value obtained from the individual force–time curve; average impulse (I_{avg}), quotient of the sum of the single-stroke impulse and the number of strokes performed during the 15 seconds tethered swim; and maximum impulse (I_{max}), highest value of the impulse of force in a single stroke.

Statistical Analyses

Descriptive data are presented as mean ± standard deviation (SD), range, and 95% confidence intervals. The normality of all distributions was verified using Shapiro–Wilk test ($p > 0.05$). To test the relationship between the variables derived from the dryland and in-water tests, the Bivariate Pearson's correlation coefficient (r) was used. The strength of the r coefficients was interpreted as follows: trivial (< 0.10), small (0.10–0.29), moderate (0.30–0.49), high (0.50–0.69), very high (0.70–0.89), or practically perfect (> 0.90).[33] All statistical analyses were performed using the software package SPSS (IBM SPSS version 24.0, Chicago, IL, USA). Figures were created using GraphPad Prism version 8 (GraphPad Software). The significance level was set at $p < 0.05$.

Results

Descriptive values of all dependent variables are depicted in Table 1. The L_0 obtained by the two-point method showed a high positive association with F_{avg} ($r = 0.523$; $p = 0.049$), but no other significant correlations were found for L_0 (**Figure 1**). Regarding v_0, high positive associations were found with 50-m performance, stroke index, stroke length, and F_{avg} ($r \geq 0.597$; $p \leq 0.026$) (**Figure 2**). Finally, A_{line} only showed a very high positive association with F_{avg} ($r > 0.725$; $p \leq 0.006$) and high positive associations with I_{avg} and I_{max} ($r \geq 0.528$; $p \leq 0.048$) when obtained via both methods (**Figure 3**).

*****(Please insert Table 1 and Figures 1-3 near here)*****

The MVD recorded against the fixed load of 60 kg showed positive high associations with stroke index and stroke length ($r \geq 0.614$; $p \leq 0.022$) and high negative association with stroke rate ($r = -0.647$; $p = 0.016$) (**Figure 4**). In contrast, the MVD recorded against the 70%1RM and the MVM obtained against the 60 kg and 70%1RM failed to show significant correlations with swimming performance, kinematics, and tethered variables (**Figure 5**).

*****(Please insert Figures 4-5 near here)*****

Discussion

This study was designed to evaluate the association of the maximal neuromuscular capacities derived from the L-V relationship (L_0, v_0, and A_{line}) and the ability to maintain high mechanical performance (MVD and MVM) during the PBP exercise with sprint swimming performance and in-water forces. The main findings of the study revealed that: (i) v_0, but not L_0 and A_{line}, presented high associations with swimming performance and kinematics, (ii) L_0, v_0 and A_{line} were highly associated with in-water forces application, (iii) the ability to maintain mechanical performance only showed significant associations with swimming kinematics for the MVD recorded during the set performed against a common absolute load (60 kg). These findings indicate that maximal neuromuscular capacities, especially v_0, have a stronger association with performance in sprint swimming and in-water force production than the ability to maintain high mechanical outputs.

Throughout the literature, conflicting results have been observed when correlating swimming performance, kinematics, and dryland strength.[10,34–36] The magnitude of the correlation seems to be influenced by methodological factors such as swimming distance, level of performance, dry-land exercise selected and/or the testing procedure conducted. Our first hypothesis was partially supported because only v_0 showed a positive association with 50-m sprint swimming performance and kinematics, whereas neither L_0 nor A_{line} obtained from the PBP exercise showed a significant correlation. Indeed, a low-volume and high-velocity resistance training program has been proven to elicit significant improvements in sprint swimming performance.[7] Similarly, Crowe et al.[9] showed no significant correlations between lat-pull down 1RM (*i.e.,* note that the correlations between L_0 and 1RM are nearly perfect) with swimming performance in male swimmers. Hence, our results could help clarify the key exercises and strength manifestations that should be prioritized in resistance training programs for the enhancement of swimmers' performance. This understanding would facilitate more efficient progress in training and consequently, VBT could emerge as a pivotal component in the overall performance development of swimmers in the gym. Regarding kinematics, only v_0 was significantly correlated with stroke length and index, probably due to the association with the hand acceleration during the underwater path.[37] Despite these encouraging results, it may differ when testing elite swimmers, as their technique level is expected to be higher which undoubtedly would influence the stroke length during front crawl and also elite might report higher dry-land strength values (*i.e.,* in this case, L_0 might explain the swimming performance and kinematic).[38,39]

Tethered swimming has been shown to assess swimmers' muscle strength and the ability to exert force in the water.[6] Nevertheless, the constrains observed during fully tethered (*i.e.,* lack of displacement) result in a unique flow that induces differences to free swimming, which translate into a higher muscle strength contribution to tethered forces than during the actual free swimming.[40] Supporting our second hypothesis, all the maximal neuromuscular variables obtained during the PBP exercise were positively associated with in water-forces, particularly for F_{avg}.[10] The swimmers' performance level may impact these results, since elite sprint swimmers take advantage at each phase of the stroke (*i.e.,* higher impulse values) and may show a higher association with impulse instead of force.[10,32] Future research should therefore explore the relationships showed in the current study with swimmers of higher performance level. Another factor potentially influencing the results is the duration of the tethered swimming test. It is noted that mean values derived from a 30 s tethered swimming test are more closely related to 50-m sprint swimming than 15 s mean values.[32] Consequently, future investigations should delve into these associations by employing varying durations of tethered swimming tests.

As estimators of the ability to maintain maximal mechanical performance, neither MVM nor MVD were significantly associated with swimming performance or in-water force production. This result should be taken with caution because the testing procedure was carried out in a 25-m pool (*i.e.,* influence of the start and the turns).[6] In the same way, 15 seconds of maximum effort during tethered swimming may not be long enough to evidence the impact of fatigue during in-water forces measurement.[10] Hence, this ability to maintain maximal mechanical performance may be more decisive for longer distances such as 100- or 200-m.[34] On the other hand, the MVD recorded during the 60 kg set showed a negative relationship with stroke rate and positive relationship with stroke length and stroke index. This fact may be explained by those swimmers which presented a higher decline in velocity had probably a higher loss of force application throughout the stroke (*i.e.,* slippery movement of the hands). This resulted in a higher stroke rate and a lower stroke length and, therefore, lower efficiency.[10] Therefore, considering the aforementioned aspects and given the relationship between peak force and velocity stability in 100-m,[41] future studies should test the association of these two variables with longer sprint swimming distances

Strength and conditioning practitioners often face the challenge of efficiently assessing numerous individuals at once within a limited timeframe. In this sense, it is crucial to prioritize the selection of assessment variables that not only demonstrate reliability, validity, and relevance but also offer ease of implementation from a practical perspective.[12,13] Recently, the two-point method applied in field conditions (*i.e.,* only two distant loads are monitored) has been proposed as a more feasible procedure to estimate the maximal neuromuscular capacities through the L-V relationship.[12,13] The main advantage of this approach is that it is less time consuming and less prone to fatigue, simplifying its implementation when dealing with multiple athletes and only one linear encoder. In the present study, the multiple-point method has been significantly associated with 6 out of 27 variables, whereas the two-point has been significantly associated with 8 out of 27 variables. Altogether, the two-point method seems to be a feasible method to daily assess the dry-land swimmers' performance during the PBP exercise. However, future studies should analyze these associations in other resistance training exercises and swimmers with different levels of performance.

Despite of the valuable results derived from this study, there are certain limitations to be considered. First, the sample size was notably limited but it is pertinent to highlight that all participants hailed from the same swimming team with a homogeneous resistance training background. This fact enables to control parameters such as previous strength experience (*e.g.,* training frequency) and training load management prior to the study onset. Second, because swimmers commonly train with free-weights, the use of a Smith machine may limit the ecological validity of our findings. However, it is essential to recognize that machine-based exercises offer more dependable measurements of movement velocity compared to free-weight exercises. Although the results are so far promising, more studies are needed to explore the associations when different equipment are used (free-weights *vs.* Smith machine) and considering swimmers of different performance levels (1-2-3 *vs.* 4-5). Third, these relationships are influenced by swimmers' technique, and although the sample used was highly controlled, future studies could attempt to quantify technique to provide additional insights in these relationships.

Finally, the maximal neuromuscular capacities obtained during the PBP exercise are significantly associated with the performance, kinematics, and in-water force from level 4 swimmers. From a practical point of view, this information may help coaches to daily assess the dry-land exercises and prescribe better training programs tailored to the specific swimming demands. However, the ability to maintain maximal mechanical performance (MVM and MVD) obtained during the PBP exercise does not seem to be related to the performance and kinematics during sprint swimming. It is important to emphasize that these findings are specifically applicable to front-crawl sprint swimming performance. Consequently, there remains ample scope for exploration within the realm of other swimming strokes and varying distances. This is particularly important given the varied contributions of maximal neuromuscular capacities and the ability to sustain high mechanical outputs across different swimming events.

Practical Applications

The inclusion of the PBP exercise can be a useful tool for daily monitoring the maximal neuromuscular capacities through the L–V relationship as well as enhance the 50-m swimming performance when moderate-to-light loads are used (*i.e.,* related with A_{line} and v_0). During practical settings, coaches should be mindful that these variables can be obtained by a faster and less-prone to fatigue procedure by implementing the two-point method. Specifically, the application of the two-point method involves three steps: (i) perform an adequate warm-up [see reference[12]] (ii), monitor the lifting velocity against two distant loads, approximately 20% and 85%1RM, and (iii) model the individual L-V relationships from the previous two experimental points to obtain the L-V relationship variables (L_0, v_0 and A_{line}).

Conclusions

Our results indicate that the maximum velocity capacity (v_0) derived from L–V relationships during the PBP exercise is highly associated with swimming performance, kinematics, and in-water force applications for level 4 swimmers. Complementary, the proxy of maximal power (A_{line}) is associated with in-water force applications. However, the maximal force (L_0) and the ability to maintain high mechanical outputs only reached significant associations for average force and stroke rate, respectively.

Acknowledgments:

This study was supported PID2022-142147NB-I00. SWIM III: Effect of the application of different specific warm-ups [PAPE: Postactivation Performance Enhancement] on muscular, physiological and technical response in competitive swimmers and funded by MCIN/AEl/10.13039/501100011033 and, as appropriate, by "ERDF A way of making Europe", by the "European Union NextGenerationEU/PRTR". Also by the Spanish Ministry of University under the pre-doctoral grant (FPU19/01137) awarded to SMM and (FPU19/02477) awarded to OLB.

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TABLE AND FIGURE CAPTIONS

Table 1. Descriptive values for the different variables considered in the study.

Figure 1. Relationship of the maximal theorical force (L_0) obtained from the multiple- and two-point methods during the prone bench pull exercise with swimming performance, swimming kinematics and in-water force production. *p*, *p*-value; *r*, Bivariate Pearson's product-moment correlation coefficient.

Figure 2. Relationship between the maximal theorical velocity (v_0) obtained from different estimation methods (multiple- and two- point method) from prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. *p*, *p*-value; *r*, Bivariate Pearson's product-moment correlation coefficient.

Figure 3. Relationship between the maximal theorical power (A_{line}) obtained from different estimation methods (multiple- and two- point method) from prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. *p*, *p*-value; *r*, Bivariate Pearson's product-moment correlation coefficient.

Figure 4. Relationship between the mean velocity decline (MVD) when different loads (60 kg and 70%1RM) are performed during the prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. *p*, *p*-value; *r*, Bivariate Pearson's product-moment correlation coefficient.

Figure 5. Relationship between the mean velocity maintenance (MVM) when different loads (60 kg and 70%1RM) are performed during the prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. *p*, *p*-value; *r*, Bivariate Pearson's product-moment correlation coefficient.

SUPPLEMENTARY FILES

Figure 1. Overview of the experimental design. 1RM, indicates one-repetition maximum.

Figure 2. Relationship between the load and the fastest mean velocity (MV) of the set during the prone bench pull exercise (PBP) when multiple-point method and two-point method are used (upper panel) and, the MV decline and MV maintenance against 60kg and 70%1RM from a representative subject (lower panel). L_0, maximum theorical load at zero velocity; v_0, maximal theorical velocity at zero load; A_{line}, area under the relationship.

Table 1. Descriptive values for the different variables considered in the study.

		Variables	Mean ± SD
Maximal neuromuscular capacities	Multiple-point method	L_0 (kg)	114.32 ± 11.77
		v_0 ($m \cdot s^{-1}$)	2.15 ± 0.13
		A_{line} ($kg \cdot m \cdot s^{-1}$)	122.84 ± 13.72
	Two-point method	L_0 (kg)	117.74 ± 13.72
		v_0 ($m \cdot s^{-1}$)	2.21 ± 0.14
		A_{line} ($kg \cdot m \cdot s^{-1}$)	129.87 ± 16.55
Maximal mechanical maintenance capacity	MVM	70%1RM (%)	92.26 ± 2.70
		60 kg (%)	93.27 ± 1.03
	MVD	70%1RM (%)	-14.03 ± 4.42
		60 kg (%)	-11.11 ± 4.50
Sprint swimming	Performance	50 m time (s)	27.06 ± 1.01
	Kinematics	SR ($cyc \cdot min^{-1}$)	54.31 ± 3.37
		SL (m)	1.94 ± 0.13
		SI ($m^2 \cdot s^{-1}$)	3.39 ± 0.29
In-water forces		F_{avg} (N)	130.70 ± 19.84
		F_{max} (N)	283.49 ± 31.24
		I_{avg} (N·s)	153.93 ± 23.30
		I_{max} (N·s)	178.58 ± 28.35

L_0: load-axis intercept; v_0: velocity-axis intercept; A_{line}: area under the load-velocity relationship line; MVM, mean velocity maintenance; MVD, mean velocity decline; 1RM: one-repetition maximum; SR: stroke rate; SL: stroke length; SI: stroke index; F_{avg}: average force; F_{max}: maximum force; I_{avg}: average impulse; I_{max}: maximum impulse.

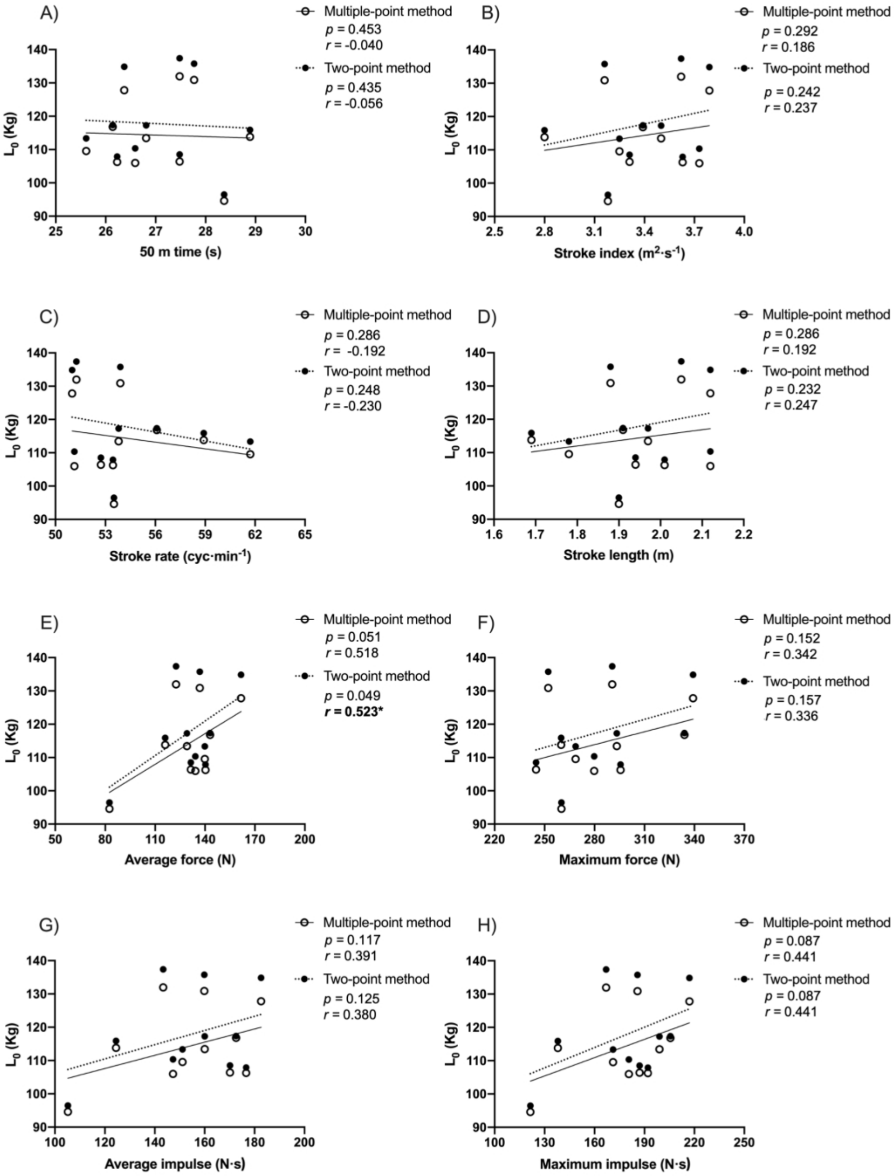

Figure 1. Relationship of the maximal theorical force (L0) obtained from the multiple- and two-point methods during the prone bench pull exercise with swimming performance, swimming kinematics and in-water force production. p, p-value; r, Bivariate Pearson's product-moment correlation coefficient.

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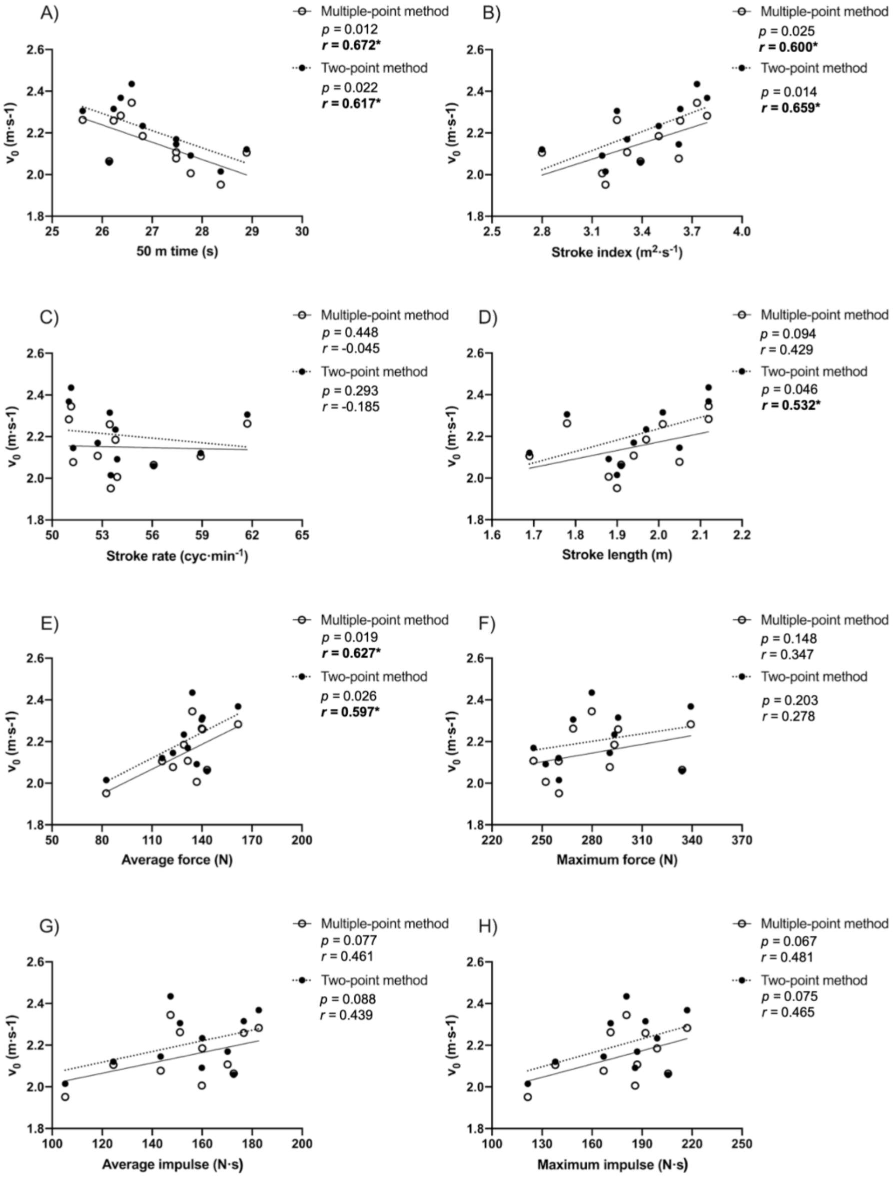

Figure 2. Relationship between the maximal theorical velocity (v0) obtained from different estimation methods (multiple- and two- point method) from prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. p, p-value; r, Bivariate Pearson's product-moment correlation coefficient.

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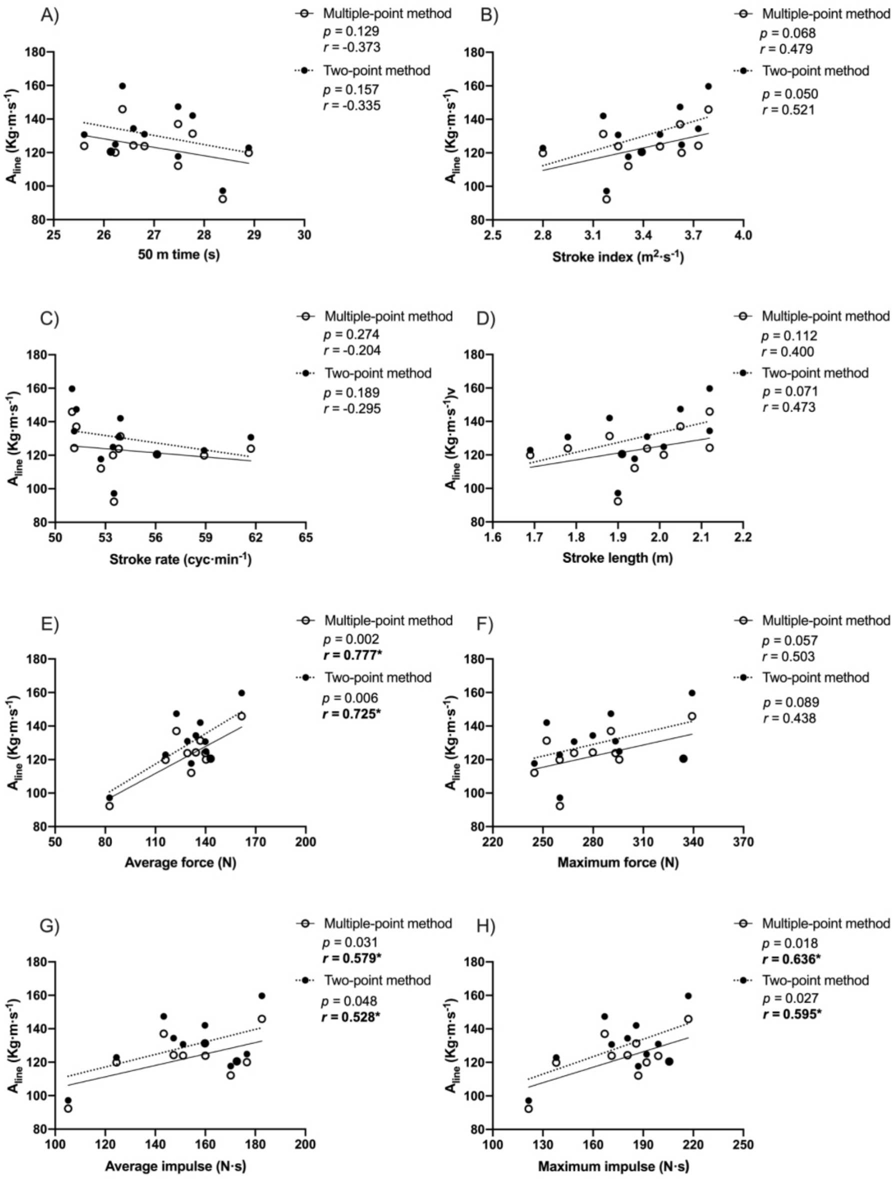

Figure 3. Relationship between the maximal theorical power (Aline) obtained from different estimation methods (multiple- and two- point method) from prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. p, p-value; r, Bivariate Pearson's product-moment correlation coefficient.

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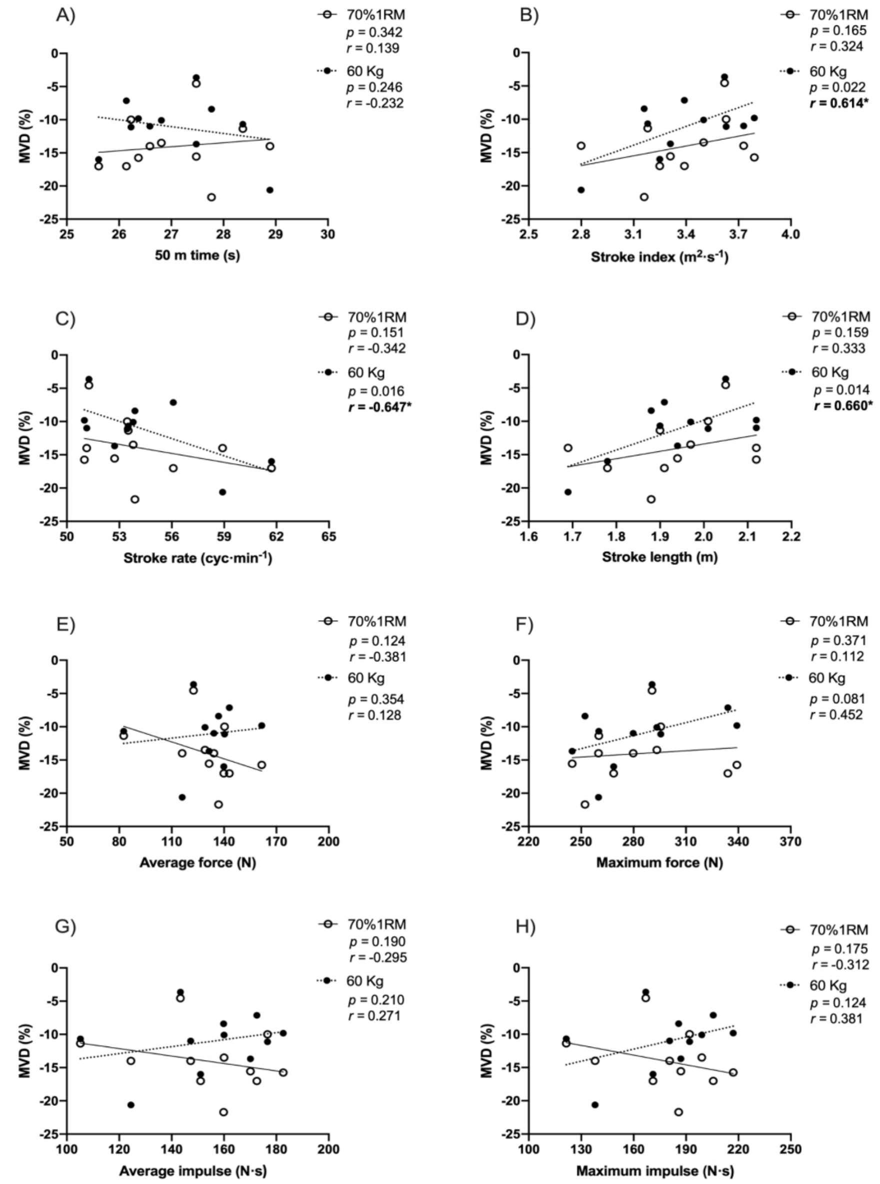

Figure 4. Relationship between the mean velocity decline (MVD) when different loads (60 kg and 70%1RM) are performed during the prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. p, p-value; r, Bivariate Pearson's product-moment correlation coefficient.

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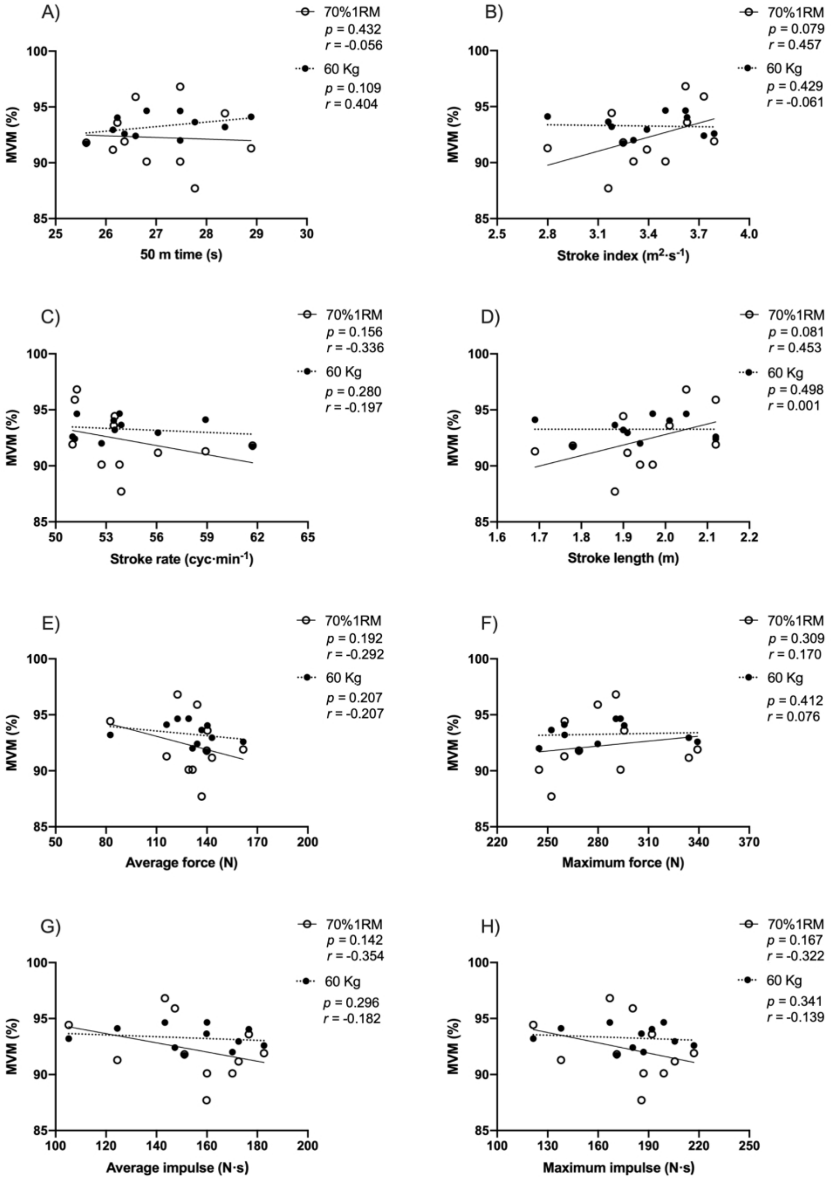

Figure 5. Relationship between the mean velocity maintenance (MVM) when different loads (60 kg and 70%1RM) are performed during the prone bench pull exercise and, swimming performance, swimming kinematics and in-water force production. p, p-value; r, Bivariate Pearson's product-moment correlation coefficient.

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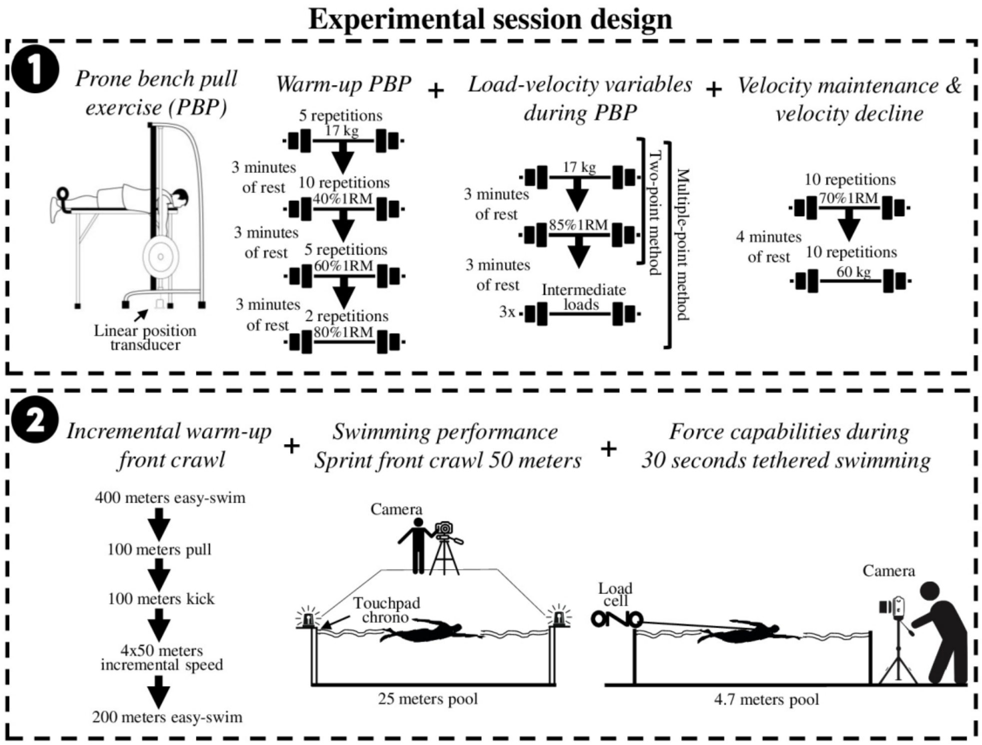

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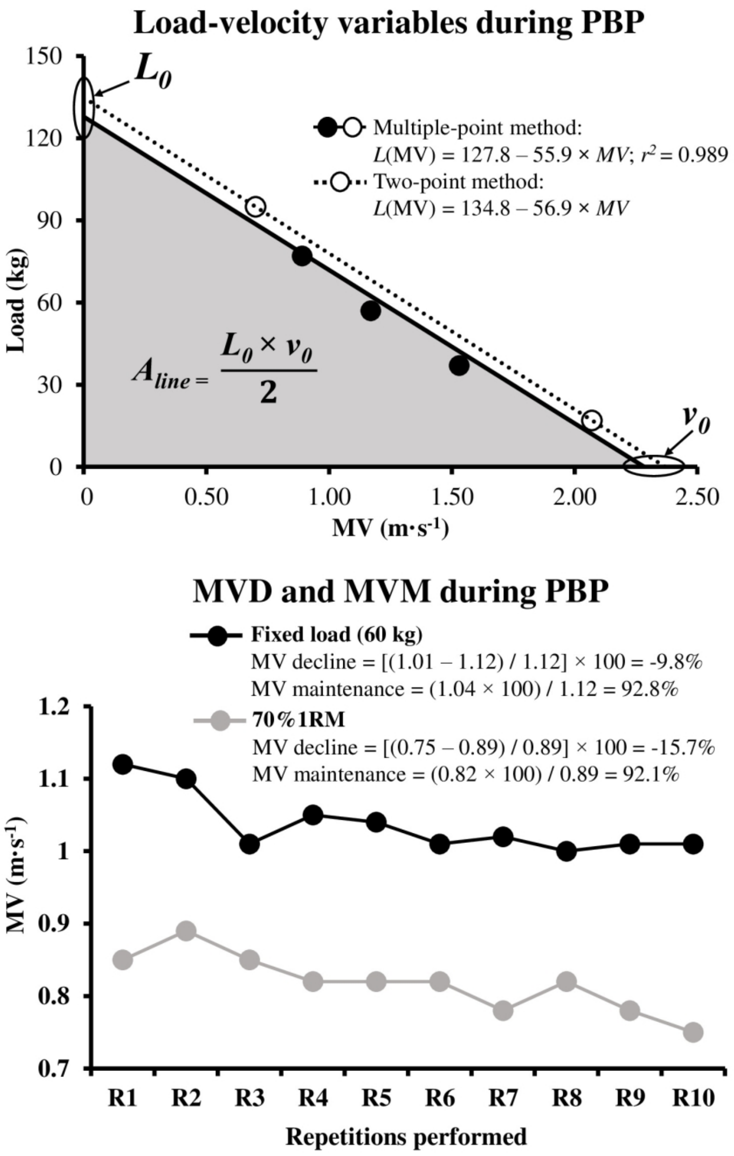

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