Muscle Synergies of The Butterfly Stroke: Comparison Between A History of Shoulder Pain During Swimming

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Abstract

This study aimed to investigate whether muscle coordination differs between swimmers with and without a history of swimmer's shoulder (SS). Muscle synergies, which can assess muscle coordination, in young elite male swimmers were analyzed using surface electromyography (EMG). Twenty elite swimmers who swam the butterfly stroke were included in this study (SS n=8; control n=12). Four muscle synergies in both groups were identified. Synergy #1, which is involved in the early pull, and Synergy #3, which is involved in the early recovery, were shown to be different synergies in both groups. In the SS group, the contribution of the internal oblique, external oblique, and rectus abdominis, which are involved in stabilizing the trunk, was low during the early pull. In the early recovery, the SS group had lower contributions of the serratus anterior, upper trapezius, and lower trapezius involved in stabilizing the shoulder girdle, and a lower contribution of the erector spinae presenting in the control group. In the rehabilitation is desirable to introduce exercises to obtain coordination of the upper limb and abdominal muscles in the early pull phase, and coordination of the periscapular muscles and erector spinae in the early recovery phase.

Introduction

The swimmer's shoulder (SS) is the most common injury in swimming^{1,2} since 91% of competitive swimmers experience it in their lifetime^{3,4}. In SS, shoulder pain is particularly frequent and is a major cause of missing practice⁵.

Swimming is an overhead sport. The highly repetitive upper limb overhead movement provides the bulk of the propulsion for all the following four major strokes: freestyle, butterfly, breaststroke, and backstroke. Elite swimmers swim 14,000 m per day, which requires >2,500 shoulder rotations per day and >16,000 per week⁶. Swim-training volume is associated with shoulder pain in adolescent competitive swimmers⁷. Hence, overuse injuries are more common than acute injuries in competitive swimmers^{8,9}{Soligard, 2017 #525}. Moreover, the rate of overuse injuries is higher than that in other sports⁸.

The SS is a painful syndrome of the anterior shoulder induced by repetitive impingement of the rotator cuff beneath the coronal acromion arch^{10,11}. Typically, this diagnosis is labeled "impingement syndrome". Studies on SS and related factors were frequently retrospective, with previous research reporting reduced endurance, lack of coordination or weakness of shoulder muscles, lack of scapular stability, poor posture, lack of trunk stability, and changes in shoulder and spinal mobility¹¹⁻¹⁴.

Electromyographic studies have been few, and they have focused on shoulder joint injuries from swimming the butterfly, freestyle, backstroke, and breaststroke¹⁵. However, considering that the previous studies were conducted in the 1990s¹⁶⁻¹⁸, competition records are rapidly improving now, and the factors of occurrence may be different. Moreover, the previous studies have focused only on the around shoulder joint muscles. The swimming motion is based on the trunk and the upper and lower limbs to obtain

propulsive power. Therefore, it is possible that not only the muscles around the shoulder joint, but also the coordination with trunk and lower limb muscles may affect the development of shoulder joint injuries.

Recently, the non-negative matrix factorization (NMF) analysis, which is based on Bernstein's concept of muscle synergy, has been used to evaluate muscle coordination^{19,20}. The NMF analysis requires electromyographic data and is divided into two factors: muscle synergy vectors (W) and temporal activation patterns (C). Muscle synergy vectors indicate muscle coordination that is a time-invariant matrix including the weights corresponding to the contribution of each muscle to the specific, while the temporal activation patterns indicate the activation timing of the muscle synergy²¹. Sports activity has also been analyzed using NMF, although studies have been limited²². Studies of NMF analysis have been conducted comparing athletes and non-athletes²³⁻²⁵, as well as before and after training interventions²⁶, although only few studies have examined the presence or absence of injury^{27,28}. In swimming, only breaststroke and underwater undulatory swimming have been subjected to muscle synergy analysis^{29,30}. No previous studies have examined muscle synergy changes in the presence or absence of injury. Here, we focused on the butterfly stroke, and this study aimed to determine whether muscle coordination of the upper, trunk, and lower limbs during the butterfly stroke in elite swimmers differs between those with and without a history of shoulder pain. The hypothesis was that swimmers with a history of shoulder pain had poor upper limb and trunk/lower limb coordination.

Materials And Methods

Participants

Here, 20 young men with a mean $\pm$ standard deviation (SD) age of 20 ± 1 years, height of 1.77 ± 0.07 m, weight of 72.1 ± 5.7 kg, and swimming experience of 13 ± 3 years, respectively, participated in this study. All participants practiced with a collegiate swimming team 10 times per week and had received a mean FINA point value of 769.0 ± 87.9 for their best records in the butterfly stroke. They were elite swimmers, one had received a medal in butterfly stroke swimming in the Rio Olympics, and one had received a gold medal in butterfly stroke swimming in Universiade competitions.

Swimmers with a history of lower limb disorders, neurological disorders, or lower limb surgery were excluded. The participants in the control group had no shoulder pain and shoulder injury in their competitive life so far, and no orthopedic injuries in all parts of the body were sustained 6 months after measurement. The SS group was defined as those with a history of shoulder joint injury within 1 year and shoulder disorder was confirmed by an orthopedic surgeon. Additionally, the swimmers in the SS group had no pain at the time of measurement in electromyographic data but had recurrent shoulder injury within 6 months of the measurement. The SS group's details are as follows: $n=8$; age, 21 ± 2 years; height, 1.77 ± 0.06 m; weight, 73.3 ± 6.1 kg; FINA point 756.9 ± 99.1 , and swimming experience 13 ± 4 years, and the control group's details are as follows: $n=12$; age, 20 ± 1 years; height, 1.77 ± 0.07 cm; weight, 71.3 ± 5.5 kg; FINA point 787.1 ± 106.4 ; and swimming experience 13 ± 2 years. No significant difference in anthropometric characteristics was observed between the two groups.

The participants were fully informed of the risks, benefits, and stresses of the study, and their written informed consent was obtained. The study was conducted in accordance with the Declaration of Helsinki and approved by the Waseda University's Research Ethics Committee (2016-267).

Sample size calculation

Since previous studies of muscle synergy analysis in swimming have compared novice and elite swimmers, with 8 swimmers in each group²⁹, a comparison was also made in this study between a control group of 12 swimmers and an SS group of 8 swimmers.

Experimental setting

Experimental trials were conducted in a 50-m indoor pool. After a 15-min warm-up with low-to-moderate intensity aerobic swimming and elements of kick and drill exercises, the participants performed a 25-m butterfly stroke at the pace of a 100-m butterfly race. They started swimming in the water with a push off from the wall.

Two cameras (high-speed camera 1394, DKH Inc., Japan) were installed at 10 m and 15 m from the wall. They filmed the sagittal movements of the swimmers and recorded videos through underwater windows at a 200-Hz sampling rate. Wireless LED markers were placed to the styloid process, lateral epicondyle of the humerus, acromion, and greater trochanter (Kirameki, Nobby Tech Inc., Tokyo, Japan) to separate the phases of the swimming cycle. The markers were placed on the right side of each participant in the control group, and on the injured side of each participant in the SS group.

EMG data

EMG data were measured using wireless EMG system (Biolog2, S&ME Inc., Tokyo, Japan), which were recorded from 12 muscles on the right side of the body in control group and in the injured shoulder's side in the SS group as follows: biceps brachii (BB), triceps brachii (TB), latissimus dorsi (LD), serratus anterior (SA), pectoralis major (PM), upper trapezius (UT), lower trapezius (LT), internal oblique (IO), external oblique (EO), rectus abdominal (RA), erector spinae (ES), and rectus femoris (RF). The electrodes were placed as follows: BB: on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit; TB: at 50% on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to the line; LD: oblique angle over the LD muscle, approximately 4 cm below the inferior tip of the scapula and midway between the spine and lateral edge of the torso; SA: vertically put in the mid-axillary line between the ribs 6 and 8; PM: 2 cm below the clavicle, precisely medial to the axillary fold; UT: at 50% on the line from the acromion to the spine on vertebra C7; LT: at 2/3 on the line from the trigonum spine to the 8th thoracic vertebra; IO: approximately 1 cm medial and inferior to the ASIS; EO: 15 cm lateral to the umbilicus; RA: 3 cm lateral to the umbilicus; ES: at 2 finger widths lateral from the spine of L1; and RF: at 50% on the line from the anterior spina iliaca superior to the superior part of the patella on the belly of the muscle corresponding to the central point between the ASIS and upper margin of the patella.

Before surface electrode attachment, the skin was rubbed with a skin abrasive and alcohol to reduce skin impedance. The electrodes were attached parallel to the impedance of the muscle fibers to a level < 2 kΩ. Disposable Ag/AgCl surface electrodes were used in pairs (BlueSensor N-00-S, METS Co., Japan). The sampling frequency was set at 1000 Hz.

Using the methodology of Kobayashi, the electrodes were waterproofed by covering with a water-resistant tape³¹.

To synchronize the video and EMG data, a synchronizer (PTS-110, DKH Inc., Japan) was connected to both trigger channels. Video and EMG data were recorded simultaneously.

2.4.2 Data analysis

Three butterfly cycle measurements were analyzed. It has been reported that extracting underwater undulatory swimming kinematics is highly reliable to analyze from the average value of three or more cycles as a representative value³². Therefore, three cycle values were analyzed in the present study. Here, one cycle was defined as the time from when the hand part entered the water to the hand part entering the water again. Assuming one stroke to be 100%, the three phases and the number of data intervals per phase were as follows. The underwater phase with the hand part in the water and the recovery phase with the water part were defined for each participant. (1) Early pull-through was defined as the beginning of hand entry into the water and ending when the humerus was perpendicular to the axis of the torso connecting the acromion and the greater trochanter. (2) Late pull-through was the beginning at the completion of early pull-through and ending as the hand left the water. (3) The recovery phase was the beginning of the hand exit and ending at hand entry. This phase was derived from a report by Pink et al.³³. The recorded EMG data were analyzed using a biomedical information software (BIMUTAS-Video, Kissei Comtec Co., Ltd., Japan). The raw data were band-pass filtered (4th order Butterworth) between 20 and 450 Hz and full wave rectified. EMG data were then normalized relative to the muscle's associated peak value data and interpolated to 201 timepoints.

Muscle synergies

A custom MATLAB (MATLAB R2020, MathWorks, Inc., Natick, MA) code was used to the linear envelope and NMF. NMF was performed to extract modules²⁰.

$$E = WC + e \cdots (1)$$

$$\min_{\substack{W>0 \\ C>0}} ||E - WC||_{FRO} \cdots (2)$$

E is a p-by-n initial matrix, “p” is the number of muscles, and “n” is the number of timepoints. The initial matrix consists of the normalized EMG data and consists of the average of three cycles for each of the

twelve muscles. E was a 12 - by - 201 matrix, W represent a p-by-s matrix and “s” is the number of synergies and represents muscle synergy. C is an s-by-n matrix which represents the activation coefficient, and “e” is a p-by-n residual error matrix. (2) shows that matrix “e,” calculated using (1) is minimized. W is a vector; it is written as $\vec{W}$ when calculated. For each participant, we repeated the analysis by varying the number of synergies between 1 and 11 and selected the least number of synergies fulfilling global variance accounted for (VAF) ^{34,35}. VAF is defined as 100× the coefficient of determination from the uncentered Pearson correlation coefficient ³⁶. We defined the standard as the VAF > 90%.

VAF was calculated using (3).

$$VAF = \left(1 - \frac{\sum_{i=1}^p \sum_{j=1}^n (e_{i,j})^2}{\sum_{i=1}^p \sum_{j=1}^n (E_{i,j})^2}\right) \times 100 \text{ [%]} \cdot \cdot \cdot (3)$$

where “i” ranges from 1 to “p,” “j” ranges from 1 to “n”. Thus, in this study, “i” was set from 1 to 12 and “j” was set from 1 and 201.

Statistics analysis

A scalar product (SP), calculated according to the formula described ³⁷, compared the synergies between the groups with and without SS. We defined the module as the same if the SP was >80%.

$$SP = \frac{\vec{W}_{SS} \cdot \vec{W}_{control}}{|\vec{W}_{SS}| |\vec{W}_{control}|} \times 100 \text{ [%]} \cdot \cdot \cdot (5),$$

where each $\vec{W}$ is the averaged vector among the participants in each group, and $\vec{W}_{SS}$ and $\vec{W}_{control}$ are $\vec{W}$ the of the groups with and without SS, respectively. SP was calculated using a custom MATLAB (MATLAB R2020; MathWorks, Inc., Natick, MA, USA).

The Shapiro–Wilk normality test with Lilliefors correction was also used to assess the normality of the data for mean swim velocity and the percentage of each phase. Swim velocity was calculated from the time at the 10m and 15m passage points. An unpaired t-test was performed to compare the mean swim velocity and the percentage of each phase between the groups. Effect sizes were calculated using Cohen’s d for the unpaired t-test. All comparisons were performed using the IBM SPSS Statistics for Windows, version 24 (IBM Corp., Armonk, NY, USA), and significance was set at p-value < 0.05.

Results

Individual Data

Table 1 presents the kinematic outcomes during butterfly swimming. Swimming velocities were $1.66 \pm 0.09 \text{ m}\cdot\text{s}^{-1}$ and $1.69 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$ for the control and SS groups, respectively. The ratios of each phase in one cycle were $35.8 \pm 6.1\%$ (control), $39.2 \pm 6.7\%$ (SS) in the early pull-through phase and $22.5 \pm 3.6\%$ (control), $20.3 \pm 3.8\%$ (SS) in the late pull-through phase. The recovery phase was $41.6 \pm 5.0\%$ (control), $40.5 \pm 6.1\%$ (SS). No significant differences on each phase were observed between the two groups (Table 1).

Muscle synergies — dimensionality

The analysis of dimensionality from the concatenation of all participants revealed that 3 to 4 muscle synergies were sufficient to reconstruct muscular activations for both groups. Figure 1 describe the relationship between the number of synergies and the global VAF, respectively. The number of synergies was set as the lowest number at which the global VAF exceeded 90%. When the number of synergies were 4, the global VAF exceeded 90% for all muscles in both groups. Therefore, the number of synergies was four in both groups.

Muscle synergies describing intermuscular coordination during the butterfly stroke

Synergy #1 was active at approximately 20–30% of one cycle of swimming motion, likely acting to early pull motion. Synergy #2 was active at approximately 40% of one cycle, likely acting to a late pull motion. Synergy #3 was active at approximately 55–60% of one cycle, likely acting to early recovery motion. Synergy #4 was active at approximately 90–100% and 0–10% of one cycle, likely acting to before and after the hand enters the water.

The similarities between muscle weighting extracted control and SS group were more than 80% for synergies, except for Synergy #1 and Synergy #3 (Figure 2). Synergy #2 and Synergy #4 had SP values of 87% and 92%, respectively, indicating similarities between the two groups. Meanwhile, the SP values for Synergy #1 and Synergy #3 were 76% and 77%, respectively, which were not consistent between both groups.

Figure 2 depicts the extracted synergies of the butterfly swimming and compares the control to SS groups. The figure on the left shows the Muscle synergy, and the right shows the activation patterns. Synergy #1 is active in the early pull phase, and muscle synergy show a higher contribution of BB, LD, PM, IO, EO, and RA in the control group, and a higher contribution of BB, TB, LD, SA, and ES in the SS group. Synergy #2 is active in late pull, and the muscle synergy factors are TB, LD, IO, EO, and RA that have a high contribution. Synergy #3 is active in the early recovery, and the muscle synergy show higher contributions of TB, SA, TU, TL, and ES in the control group and of IO, EO, RA, and RF in the SS group. The

activity of Synergy #4 increases before and after the hand entered the water, and the contribution of TB, TU, TL, ES, and RF was high.

Discussion

This study is the first to examine the differences in the muscle coordination of the shoulder, trunk and lower limb muscles between swimmers with and without SS. The main findings of this study were that the muscle coordination was different between swimmers with and without SS in early pull phase and early recovery phase. The number of synergies in each group was four, with synergies active in the early pull (Synergy #1), late pull (Synergy #2), early recovery (Synergy #3), and before and after water entry (Synergy #4). The most interesting finding of this study was that among these synergies, Synergy #1, and Synergy #3, which act during the early pull and early recovery, differed between both groups.

Synergy #1 is involved in the early pull, and the muscle synergy differed between both groups. During the early pull motion, the control group had higher contributions from the upper limb and trunk muscles, while the SS group had higher contributions from the upper limb muscles and ES and lower contributions from the IO, EO, and RA, which are involved in trunk stability. In the early pull motion, the water pressure on the palmar region generated an extension moment in the trunk. In the control group, the abdominal muscles resisted the disturbance, whereas in the SS group, the contribution of them was lower and the contribution of the ES, the trunk extensor, was higher. In the SS group, the contribution of the ES was higher because the coordination of the abdominal and upper limb muscles was disrupted at the timing of the early pull when the upper limb captured the water, and the SS group was unable to resist the extension moment applied to the trunk during water entry. These results suggest that the contribution of the BB, TB, SA, and LD are increased in the SS group, resulting in a greater load on the upper extremities.

Synergy #2 was active at approximately 40%, likely acting to a late pull motion. The muscle weightings were high for TB, LD, IO, EO, and RA; TB and LD were reported to be active during late pull in the previous studies³³. In addition to these muscles, IO, EO, and RA were high, and it has been reported that these muscles acted in the dolphin kick movement³⁰. Therefore, In late pull, the muscle coordination of TB and LD involved in the pull movement and IO, EO, and RA involved in the kick movement is important to improve the coordination between the dolphin kick motion and the pull motion.

Synergy #3 was involved in early recovery, and the muscle synergies differed between both groups. At this timing, after generating propulsive force by elbow extension, shoulder abduction and flexion are initiated from the shoulder joint extension position. In the SS group, the contribution of the SA, UT, and LT, which are involved in upward rotation of scapula in the control group, was low, while the contribution of the trunk flexor muscles was high. In the SS group, because of insufficient upward rotation of the scapula in the early recovery phase, which is the initial phase of shoulder joint elevation and abduction, the activities of TU, TL, and LD are increased in Synergy #4 before and after water entry, when the flexion and abduction angles are around 180 degrees. At this timing, the upper limb is in a flexion/internal rotation position which is similar to Neer's test position, a shoulder joint impingement test³⁸. Excessive activity of

UT and decreased activity of MT, LT, and SA were observed in asymptomatic healthy individuals with a shoulder impingement syndrome^{39,40}. Therefore, the contribution of UT is necessary for upward rotation of the scapula in early pull (Synergy #3), but the contribution of UT is considered to induce SS before and after hand entry (Synergy #4), when the upper limb flexion angle is large and the subacromion space is narrow. Based on the results of Synergy #3 and #4, it is important to promote upward rotation of the scapula by coordinating the UT, LT, and SA in the early stage of the recovery motion to prevent SS. In addition, the contribution of the trunk flexors in the SS group in Synergy #3 was thought to be active to resist the extending moment of the upper body due to the kicking motion, but in the control group, even though the trunk tended to flex due to the kicking motion, the ES was active, which extended the spine and facilitated the upward rotation of the scapula during early recovery, which is also an important factor in SS prevention.

Integrating the results of this study, it is important to introduce not only rehabilitation around the shoulder joint but also exercises to gain coordination between the periscapular and trunk muscles for shoulder rehabilitation in swimmers. Specifically, it is important to introduce exercises to gain coordination between the upper extremities and the abdominal muscle groups of the trunk during the initial pull, and between the muscles around the scapula and the ES during the early recovery phase.

This study has limitations that should be noted. A full motion analysis was not performed because of only two underwater high-speed cameras, we could not evaluate the motion 3D. Here, motion analysis is used only for phase division and swim speed calculation. If the motion analysis was firmly performed, the mechanism of shoulder injury occurrence could be studied. Moreover, this study evaluated high level participants. Therefore, the results cannot be generalized to other populations like low level or junior or master's swimmer. Vaz et al., who compared the synergies obtained during a breaststroke cycle between elite and beginner swimmers, found that the timing of water propulsion was earlier in beginner swimmers²⁹. This report emphasized that synergies vary according to the expertise level. Therefore, the mechanism of shoulder injury occurrence may differ depending on the level of competition and the generation. Moreover, swimmers with a history of shoulder injuries had no pain at the time of measurement, and those who relapsed later were assigned to the SS group. However, the present study is not a prospective study, so the risk factors cannot be specified. In the future, a prospective cohort study should be introduced, and further investigation is necessary.

Conclusions And Perspectives

A comparison of muscle coordination in butterfly swimmers with and without a history of swimmer's shoulder revealed that coordination differed between Early pull phase and early recovery phase. In the rehabilitation of the butterfly swimmer's swimming shoulder, it is important to gain coordination not only with the shoulder joint muscles but also with the trunk muscles. It is necessary to introduce exercises to gain coordination between the upper limb and trunk abdominal muscles in early pull phase, and between the muscles around the scapular and the erector spinae muscles in the early recovery phase.

Declarations

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Author Contributions

Y.M. and K.K. designed research; Y.M., N.M., H.A., T.K., S.I and K.O. performed experiments; N.M prepared experimental setup; Y.M. analyzed data; and All authors wrote the paper.

Data availability statement

The datasets analyzed during the current study are available from the first or corresponding author on reasonable request.

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Competing interests

The authors declare no competing interests.

References

1. Kerr, Z. Y. *et al.* Epidemiology of National Collegiate Athletic Association men's and women's swimming and diving injuries from 2009/2010 to 2013/2014. *Br J Sports Med* **49**, 465–471, doi:10.1136/bjsports-2014-094423 (2015).
2. Mountjoy, M. *et al.* Sports injuries and illnesses in the 2009 FINA World Championships (Aquatics). *Br J Sports Med* **44**, 522–527, doi:10.1136/bjsm.2010.071720 (2010).
3. Wolf, B. R., Ebinger, A. E., Lawler, M. P. & Britton, C. L. Injury patterns in Division I collegiate swimming. *Am J Sports Med* **37**, 2037–2042, doi:10.1177/0363546509339364 (2009).
4. Sein, M. L. *et al.* Shoulder pain in elite swimmers: primarily due to swim-volume-induced supraspinatus tendinopathy. *Br J Sports Med* **44**, 105–113, doi:10.1136/bjsm.2008.047282 (2010).
5. Weldon, E. J., 3rd & Richardson, A. B. Upper extremity overuse injuries in swimming. A discussion of swimmer's shoulder. *Clin Sports Med* **20**, 423–438 (2001).
6. Pink, M. M. & Tibone, J. E. The painful shoulder in the swimming athlete. *Orthop Clin North Am* **31**, 247–261, doi:10.1016/s0030-5898(05)70145-0 (2000).
7. Feijen, S., Tate, A., Kuppens, K., Claes, A. & Struyf, F. Swim-Training Volume and Shoulder Pain Across the Life Span of the Competitive Swimmer: A Systematic Review. *J Athl Train* **55**, 32–41, doi:10.4085/1062-6050-439-18 (2020).

8. Soligard, T. *et al.* Sports injury and illness incidence in the Rio de Janeiro 2016 Olympic Summer Games: A prospective study of 11274 athletes from 207 countries. *Br J Sports Med* **51**, 1265–1271, doi:10.1136/bjsports-2017-097956 (2017).
9. Schroeder, A. N. *et al.* Epidemiology of overuse injuries among high-school athletes in the United States. *J Pediatr* **166**, 600–606, doi:10.1016/j.jpeds.2014.09.037 (2015).
10. Tate, A., Turner, G. N., Knab, S. E., Jorgensen, C., Strittmatter, A., & Michener, L. A.. Risk factors associated with shoulder pain and disability across the lifespan of competitive swimmers. *Journal of athletic training* **47**, 149–158 (2012).
11. Hill, L., Collins, M. & Posthumus, M. Risk factors for shoulder pain and injury in swimmers: A critical systematic review. *Phys Sportsmed* **43**, 412–420, doi:10.1080/00913847.2015.1077097 (2015).
12. Struyf, F., Tate, A., Kuppens, K., Feijen, S. & Michener, L. A. Musculoskeletal dysfunctions associated with swimmers' shoulder. *Br J Sports Med* **51**, 775–780, doi:10.1136/bjsports-2016-096847 (2017).
13. Bak, K. The practical management of swimmer's painful shoulder: etiology, diagnosis, and treatment. *Clin J Sport Med* **20**, 386–390, doi:10.1097/JSM.0b013e3181f205fa (2010).
14. Wanivenhaus, F., Fox, A. J., Chaudhury, S. & Rodeo, S. A. Epidemiology of injuries and prevention strategies in competitive swimmers. *Sports Health* **4**, 246–251, doi:10.1177/1941738112442132 (2012).
15. Martens, J., Figueiredo, P. & Daly, D. Electromyography in the four competitive swimming strokes: a systematic review. *J Electromyogr Kinesiol* **25**, 273–291, doi:10.1016/j.jelekin.2014.12.003 (2015).
16. Scovazzo, M. L., Browne, A., Pink, M., Jobe, F. W. & Kerrigan, J. The Painful Shoulder during Freestyle Swimming - an Electromyographic Cinematographic Analysis of 12 Muscles. *American Journal of Sports Medicine* **19**, 577–582, doi:Doi 10.1177/036354659101900604 (1991).
17. Ruwe, P. A., Pink, M., Jobe, F. W., Perry, J. & Scovazzo, M. L. The Normal and the Painful Shoulders During the Breaststroke. *Am J Sports Med* **22**, 789–796, doi:10.1177/036354659402200610 (1994).
18. Perry, J., Pink, M., Jobe, F. W., Kerrigan, J., Browne, A., & Scovazzo, M. L. The painful shoulder during the backstroke- an EMG and cinematographic analysis of 12 muscles. *Clinical journal of sport medicine* **2**, 13–20 (1992).
19. Ting, L. H., and Chvatal, S. A. Decomposing Muscle Activity in Motor Tasks: Methods and Interpretation. *Motor Control: Theories, Experiments, and Applications*, 102–138 (2010).
20. Lee, D. D. & Seung, H. S. Learning the parts of objects by non-negative matrix factorization. *Nature* **401**, 788–791, doi:10.1038/44565 (1999).
21. Zelik, K. E., La Scaleia, V., Ivanenko, Y. P. & Lacquaniti, F. Can modular strategies simplify neural control of multidirectional human locomotion? *J Neurophysiol* **111**, 1686–1702, doi:10.1152/jn.00776.2013 (2014).
22. Taborri, J. *et al.* Feasibility of Muscle Synergy Outcomes in Clinics, Robotics, and Sports: A Systematic Review. *Appl Bionics Biomech*, 3934698, doi:10.1155/2018/3934698 (2018).

23. Turpin, N. A., Guével, A., Durand, S. & Hug, F. Effect of power output on muscle coordination during rowing. *European Journal of Applied Physiology* **111**, 3017–3029, doi:10.1007/s00421-011-1928-x (2011).
24. Shaharudin, S., & Agrawal, S.. Muscle synergies during incremental rowing VO₂max test of collegiate rowers and untrained subjects. *The Journal of sports medicine and physical fitness* **56**, 980–989 (2016).
25. Santos, P. D. G. *et al.* Intermuscular Coordination in the Power Clean Exercise: Comparison between Olympic Weightlifters and Untrained Individuals-A Preliminary Study. *Sensors (Basel)* **21**, doi:10.3390/s21051904 (2021).
26. Silva, P. B., Oliveira, A. S., Mrachacz-Kersting, N. & Kersting, U. G. Effects of wobble board training on single-leg landing neuromechanics. *Scand J Med Sci Sports* **28**, 972–982, doi:10.1111/sms.13027 (2018).
27. Allison, K. *et al.* Hip abductor muscle activity during walking in individuals with gluteal tendinopathy. *Scand J Med Sci Sports* **28**, 686–695, doi:10.1111/sms.12942 (2018).
28. Sekine, C., Matsunaga, N., Okubo, Y., Hangai, M. & Kaneoka, K. Lumbar Intervertebral Disc Degeneration Does Not Affect Muscle Synergy for Rowing Activities. *Appl Bionics Biomech*, 6651671, doi:10.1155/2021/6651671 (2021).
29. Vaz, J. R. *et al.* Muscle coordination during breaststroke swimming: Comparison between elite swimmers and beginners. *J Sports Sci* **34**, 1941–1948, doi:10.1080/02640414.2016.1143109 (2016).
30. Matsuura, Y., Matsunaga, N., Iizuka, S., Akuzawa, H. & Kaneoka, K. Muscle Synergy of the Underwater Undulatory Swimming in Elite Male Swimmers. *Front Sports Act Living* **2**, 62, doi:10.3389/fspor.2020.00062 (2020).
31. Kobayashi, K., Kaneoka, K., Takagi, H., Sengoku, Y., Takemura, M.. Lumbar Alignment and Trunk Muscle Activity during the Underwater Streamline Position in Collegiate Swimmers. *Journal of Swimming Research* **23**, 33–43 (2015).
32. Atkison, R. R., Dickey, J. P., Dragunas, A. & Nolte, V. Importance of sagittal kick symmetry for underwater dolphin kick performance. *Hum Mov Sci* **33**, 298–311, doi:10.1016/j.humov.2013.08.013 (2014).
33. Pink, M., Jobe, F. W., Perry, J., Kerrigan, J., Browne, A., Scovazzo, M. L. The normal shoulder during the butterfly swim stroke. An electromyographic and cinematographic analysis of twelve muscles. *Clinical orthopaedics and related research* **288**, 48–59 (1993).
34. Torres-Oviedo G, M. J., Ting LH.. Muscle synergy organization is robust across a variety of postural perturbations. *Journal of Neurophysiology* **96**, 1530–1546 (2006).
35. Hug, F. T. N. G., A.; Dorel, S. Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of Applied Physiology* **108**, 1727–1736 (2010).
36. Tresch, M. C., Cheung, V. C. & d'Avella, A. Matrix factorization algorithms for the identification of muscle synergies: evaluation on simulated and experimental data sets. *J Neurophysiol* **95**, 2199–

2212, doi:10.1152/jn.00222.2005 (2006).

37. Cheung, V. C. *et al.* Muscle synergy patterns as physiological markers of motor cortical damage. *Proc Natl Acad Sci U S A* **109**, 14652–14656, doi:10.1073/pnas.1212056109 (2012).
38. Neer, C. S. Impingement lesions. *Clinical Orthopaedics and Related Research* **173**, 70–77 (1983).
39. Chester, R., Smith, T. O., Hooper, L. & Dixon, J. The impact of subacromial impingement syndrome on muscle activity patterns of the shoulder complex: a systematic review of electromyographic studies. *BMC Musculoskelet Disord* **11**, 45, doi:10.1186/1471-2474-11-45 (2010).
40. Ludewig, P. M. & Braman, J. P. Shoulder impingement: biomechanical considerations in rehabilitation. *Man Ther* **16**, 33–39, doi:10.1016/j.math.2010.08.004 (2011).

Table

Table 1 Kinematic variables measured during the butterfly swimming strokes

Variables	Unit	Control	Shoulder pain	p-value	Effect size
Swimming velocity	(m·S ⁻¹)	1.66±0.09	1.69±0.06	0.44	0.18
Early pull through phase	(%)	35.8±6.1	39.2±6.7	0.26	0.27
Late pull through phase	(%)	22.5±3.6	20.3±3.8	0.20	0.30
Recovery phase	(%)	41.6±5.0	40.5±6.1	0.66	0.08

The swimming velocity and rate of each phase were not significantly different between the two groups.

Figures

Figure 1

The number of synergies was set as the lowest number at which the global variance accounted for (VAF) exceeded 90%. When the number of synergies were 4, the global VAF exceeded 90% in the control and SS groups.

Figure 2

The muscle synergy vectors are shown at the left side of the figure aligned to the corresponding activation coefficient. The synergy activation coefficients are shown in the right side of the figure. BB, biceps brachii; TB, triceps brachii; LD, latissimus dorsi; SA, serratus anterior; PM, pectoralis major; UT,

upper trapezius; LT, lower trapezius; IO, internal oblique; EO, external oblique; RA, rectus abdominal; ES, erector spinae; RF, rectus femoris.