A study on motion characteristics of tethered swimming
― Searching potentiality as a fitness training ―

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抄　録
本研究は，牽引泳を体力トレーニングに活用するための基礎資料を提供することを目的とした。そのため、２つの水泳技能レベルグループに対して牽引負荷を設定し、牽引負荷を用いたインターバル泳、時間泳、レジステッド泳およびアシステッド泳を行わせ、生理・知覚的調査および泳ぎの構造変化について調べた。その結果は以下の通りであった。
１）牽引負荷45%max 程度のインターバル泳では、両グループともに泳ぎの構造的変化が小さく、生理・知覚的指標が定常的推移を示し、体力トレーニングとしての活用の可能性が示唆された。
２）時間泳では、両グループともに35%max 程度の牽引負荷が最も泳ぎの構造的変化が小さく、生理・知覚的指標が定常推移を示し、体力トレーニングとしての活用の可能性が示唆された。
３）レジステッド泳では通常の泳ぎに比較して筋の活動が顕著となり，アシステッド泳では通常の泳ぎに近似した筋の活動様相を示した。水泳競技者にレジステッド泳を活用する場合、泳ぎの構造的変化を避けるために適正な負荷設定が重要である。また、水泳実践者への活用は避けた方がよいと考えられた。

キーワード：牽引泳、インターバル泳、時間泳、生理的指標、知覚的指標、泳ぎの構造、体力トレーニング、可能性
Keywords：Tethered swimming, Fitness training, Physiological parameters, Perceived Index, Stroke mechanics

Ⅰ．Introduction

Tethered swimming was first reported by Liljestrand et al.[1] when they tethered a swimmer to a boat to measure body resistance and oxygen uptake. From then on, the technique was used to measure swimming efficiency and power, reported by Karpovich[2] as well as Karpovich and Pestrecov[3] among others. In recent years, there are studies on the changes of stroke mechanics and physiological response using elastic tether attached at the poolside, such as an investigation conducted by Y. Shibata et al.[4].

On tethered swimming as a part of competitive swimming training, Magel[5] reported measurement results of the propulsive force of tethered swimmers. As shown in a report by Maglischo et al.[6], physiological and biomechanical studies were conducted throughout the 1970s in order to utilize tethered swimming as part of swimming training. The thinking behind this arose from questions that the muscle training in on-land training room situations may not be appropriate for muscle activity of swimming[7] [8] or appropriate effects for swimming may not be obtained from the land-based muscle training point of view[9].

In recent years, tethered swimming in which a swimmer wears a belt with a rope that is attached to a weight at the other end via pulleys is used for swimming training. An investigation into the effect of tethered training on forward crawl stroke mechanics by Maglischo et al.[6] found an undesirable effect on stroke, however the comparison between assisted and resisted swimming by the same author [10] in the next year reported improvements of stroke mechanics in assisted swimming.

Since then, there have been a number of studies of the application of tethered swimming as a swimming training method[4]. In order to develop and popularize tethered swimming as a new training method, it is necessary to clarify the characteristics of biomechanics during tethered swimming training as well as other investigations on motion analysis and heart rate changes. With these in mind, the present study investigated the physical response (physiological and psychological aspects) of tethered swimmers on various conditions such as load, tethering method and time. It also analyzed stroke mechanics from recorded video footages and muscle activities of tethered swimming.

The purpose of this study was to provide basic data to utilize tethered swimming as a swimming training method. Subjects with different swimming skill levels were given individual loads and a set time during on-the-spot stationary tethered swimming to investigate and analyze their influence on physical responses and stroke mechanics.

Ⅱ. Methods

1. Subjects

A total of 8 swimmers, 2 male and 2 female elite competitive swimmers of the Japan championship qualifiers, as well as 2 male and 2 female healthy adults who were daily swimming activists, participated in the study. Anthropometric data and tethered loads of each subject are shown in the Table 1.

Table 1. Subjects and Tethered loads

	Subject	Age (Yrs)	Height (cm)	Weight (kg)	50mCrawl (sec)	Tethered Load (kg) (Low Med. High)	Tethered Load (kg) (Interval)	M T F (kg)
Male	1	22	181.0	75.0	23” 2	5, 6, 7	7	23.5
	2	20	173.0	80.0	25” 5	5, 6, 7	7	21.0
	3	20	169.5	65.0	28” 4	4, 5, 6	6	15.0
	4	24	167.5	53.0	29” 0	3, 4, 5	5	13.5
Female	5	20	168.5	55.5	27” 0	3, 4, 5	5	13.2
	6	20	154.0	48.0	28” 5	3, 4, 5	5	13.1
	7	25	163.5	56.5	33” 5	2, 3, 4	4	10.0
	8	26	168.9	56.0	32” 0	2, 3, 4	4	12.0

※ Tethered loads: Low(25%max), Medium(35%max), High(45%max), MTF: Max. of tethered force.

Prior to the experiment, the agreement of the subjects was obtained after providing an explanation of the contents of the study. The study was presented to and given approval from the ethics board of the Tokyo Gakugei University.

2. Modes of tethered swimming

The subjects were instructed to perform on-the-spot stationary interval tethered swimming (ITS), 4 minutes tethered swimming (4TS), resisted swimming (RS), assisted swimming (AS), and maximum tethered swimming (MTS). Maximum tethered force (MTF) was measured during maximum effort swimming.

As shown in Fig.1, the subjects swam, with a given cue, wearing a belt with a non-elastic cord (dia.5mm) with a weight at the other end via pulleys. During ITS and 4TS trials, the subjects were instructed to stay on the mark, shown at the bottom of the pool, as much as possible, minimizing going forward or backward. For RS and AS trials, measurements were taken for the distance of 15 meters each, 5m to 20m from the start-wall for RS and 20m to 5m from the start-wall for AS.

To obtain control samples, the subjects were also instructed to perform front crawl swimming without tethered (FS) at approximately 80% of the maximum effort. 80% was set considering the utilization of the training as basic endurance training. DVD footage of each subject's FS was recorded from the side and an electromyogram was also taken.

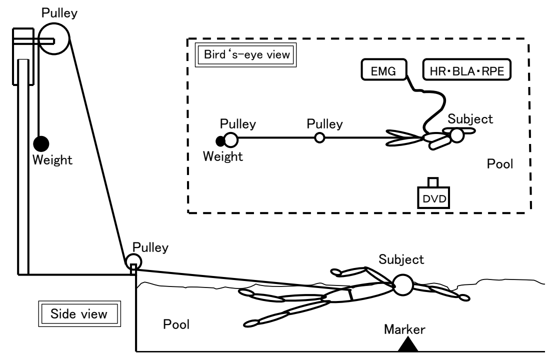


Figure 1. Experimental measurements figure

As for ITS trials, the subjects were instructed to perform crawl stroke, pulling approximately 45% of their maximum load (45%max) in a set of 10 repeated sessions consisting of 35 seconds swimming and 20 seconds rest. A marker was placed at the bottom of the swimming pool for the subject, who was instructed to swim on the spot as much as possible without going forward or backward. The largest loads, determined in a previous study [11) 12)], were set as follows; 7kg for male elite swimmers, 5kg for female elite swimmers, 5kg for male daily swimming activists and 4kg for female daily swimming activists. The session time is set within a range where HR of 135 – 160bpm is obtained and aerobic evaluation can be made.

As for 4TS, 3 kinds of load, low at 25%max, medium at 35%max and high at 45%max were set.

That means 5kg, 6kg, 7kg for elite male swimmers, 3kg, 4kg, 5kg for elite female swimmers, 3kg, 4kg, 5kg for male daily swimming activists and 2kg, 3kg, 4kg for female daily swimming activists. A marker was placed at the bottom of the swimming pool for each condition and the swimmers were instructed to swim 4 minutes on the spot without going forward or backward. The measurements were terminated when the set time was up or a swimmer lost control of staying on the spot with a wider variety of forward or backward motion.

The rationale for setting the time at 4 minutes is based on a previous study [13] that the steady-state-value of blood lactate accumulation can be estimated from 4 minutes of exercise load. The setting of the loads were computed using the same previous study as ITS trials, making sure that the load for each subject in each condition is within the appropriate range that is expected to produce appropriate aerobic exercise for 4 minutes.

As for RS and AS trials, the loads were set at 45%max, with the subjects pulling the loads in RS trial and being pulled in AS trial for about 20m which was the lead length attached to the electromyography (EMG) amp. The video footages and EMG that were recorded between from 5m to 20m, which is from the start point to were analyzed.

3. Measuring methods

MTF, Heart rate (HR), Blood lactate accumulation (BLA), and Rating of perceived exertion (RPE) were measured and each trial was video recorded. Fig.1 and Fig.2 show the measuring device diagram and the trial protocol.

As for the MTF, a subject, who wore a non-elastic rope (dia.16mm), was instructed to swim with maximum effort for 10 seconds. their MTF was measured using a spring scale that is attached at the other end of the rope.

The index of the spring scale was filmed by DVD camera and the value was read in slow motion replay. The maximum load for each subject is obtained from the mean value of the maximum tethered forces at every 3-stroke-cycle (6 strokes of right and left) after the first 3 strokes.

A bipolar chest lead type ECG (Fukuda co., DS-504) and a transmitter (Fukuda co., LX-3220) were used to measure HR. The HR of each subject was measured from the time of the warm-up to 3 minutes after each trial.

Blood samples from the subjects' fingertips were taken at rest, 1 minute and 3 minutes after completing ITS and 4TS trials were analyzed using a BLA analysis instrument (Arkray co., Lactate Pro).

Borg's RPE Scale Japanese language version [14] was used to measure perceived exertion for each subject immediately after completing ITS and 4TS trials.

As for stroke mechanics, the video footages were analyzed using a chronograph instrument (Nielsen-Kellerman) to obtain stroke rate (SR). The samples extracted were the last 5 seconds of completing each trial for MTS, FS and ITS trials and the last 5 seconds of every minute in 4TS trials.

A fixed line electromyogram (EMG) instrument (DKH) was used to take measurements of muscle activities during FS, MTS, ITS, 4TS, RS and AS trials, on right M.biceps brachii, M.triceps brachii, M.teres major and M.trapezius muscles. EMG measurements and video footages were synchronized using a time-checker manufactured by DKH by pushing the check button every time the right hand goes into water and superimposing the pulses on EMG. Root mean square (RMS) values were computed by integration of 3 stroke cycles (6 strokes of right and left). The RMS values obtained by FS trial were used to standardize other modes of swimming in percentile figures.

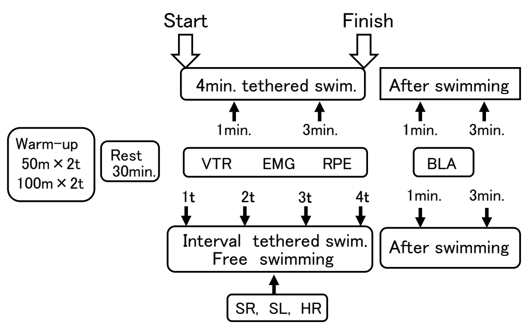


Figure 2. Protocol of this experiment

4．Statistical processing

The mean values and standard deviations of HR, BLA, RPE, stroke rate (SR) and stroke length (SL) for the ITS and 4TS trials were obtained. The Student's *t*-was conducted on the parameters obtained by the different trial conditions, and a one-way analysis of variance was conducted for HR and SR during ITS tr1als. These statistical processing were taken to determine the changes of RMS values by trial conditions, skill levels and genders. The significance level was set as $p<0.05$.

Ⅲ．Results

1．Free Swimming (FR) and Maximum tethered Swimming (MTS)

Fig.3-①〜⑥ shows EMGs of FS, AS, RS, MTS, ITS and 4TS trials. For FS trial, the muscle activity patterns and the mechanism were investigated. Using RMS values as the baseline, all EMGs were standardized. For MTS trial, the muscle activity patterns and the mechanism were investigated. They were used as the baseline for determining the %max for each condition.

2．Interval Tethered Swimming (ITS)

ITS trials were conducted by having a subject swim with 45%max load in a set of 10 repeated sessions consisting of 35 seconds swim and 20 seconds rest. Significant differences in terms of HR changes during ITS for all the subjects were observed in the measurements from the rest to the third session, however from the third session on, each subject showed a stabilizing tendency without demonstrating any significant difference. Table 2 shows physiological data taken at the completion of ITS trials.

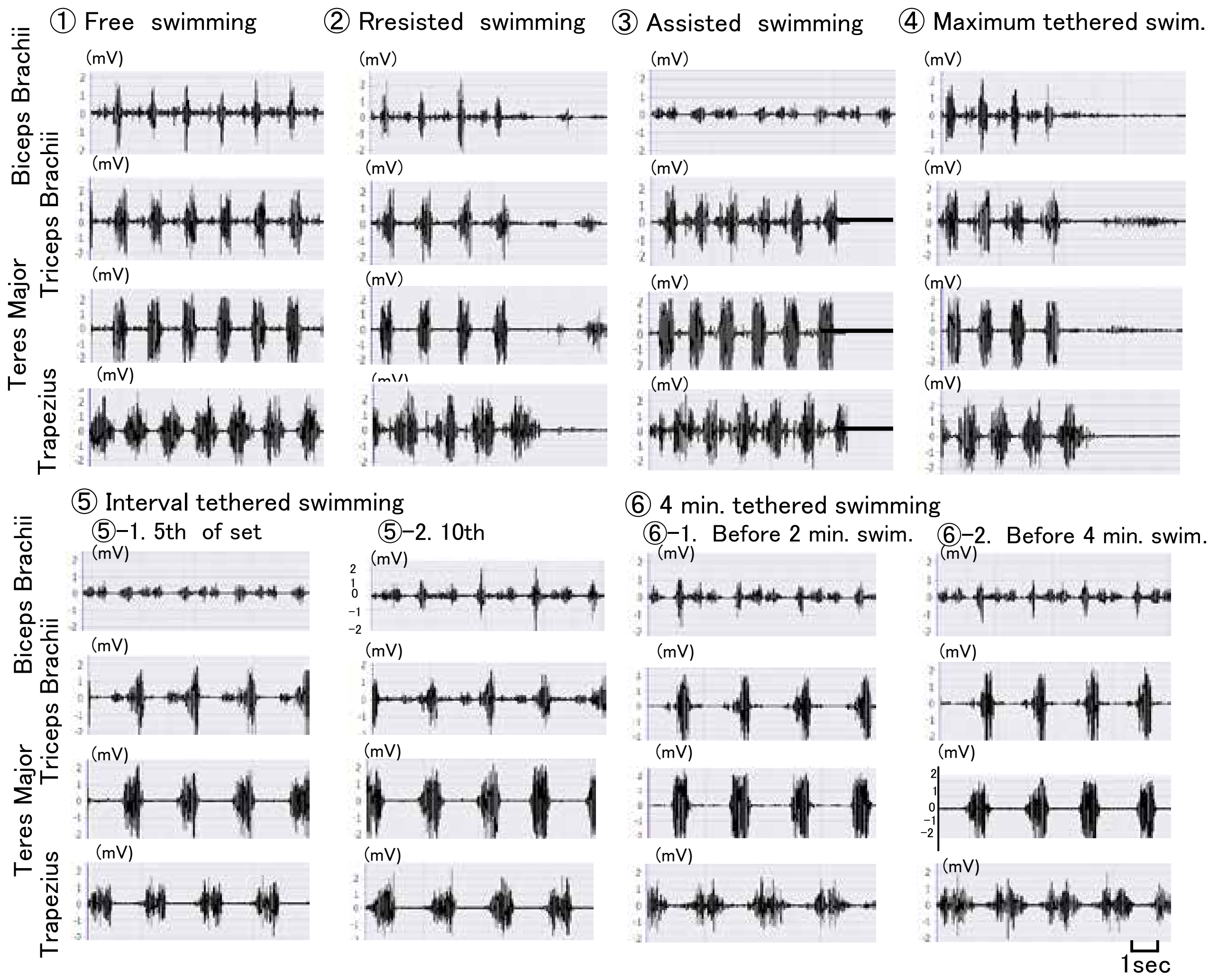


Figure 3. Comparison of EMG during swimming used tethering devices

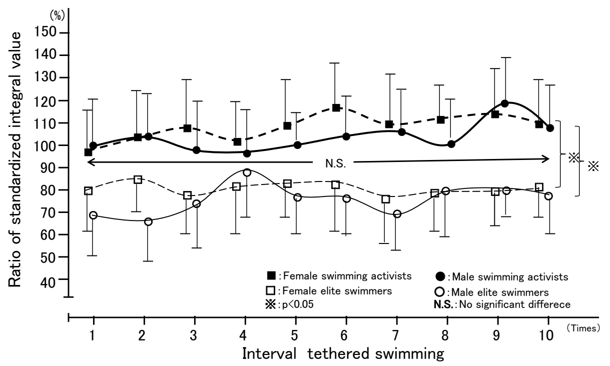
Table 2. Measurments of interval tethered swimming and 4min. tethered swimming

	Subject	Rest		Interval Tethered Swimming				4min. Tethered swimming								
								H R			B L A			R P E		
		HR	BLA	Load	HR	BLA	RPE	Low	Med	High	Low	Med	High	Low	Med	High
Male	1	60	1.1	7	138	4.3	13	99	132	156	5.0	7.7	11.8	9	11	13
	2	60	1.2	8	126	5.0	14	84	96	136	1.3	5.2	7.2	12	12	14
	3	63	1.2	6	144	5.8	15	98	132	153	4.3	9.1	10.3	11	13	15
	4	66	0.9	5	144	5.8	16	120	112	168	6.6	10.2	10.9	13	15	19
Female	5	68	1.1	5	146	4..2	14	96	102	156	1.3	2.1	5.7	7	14	15
	6	70	1.2	4	143	4.3	14	108	126	150	1.3	2.7	7.4	12	13	14
	7	66	1.1	4	150	4.9	16	114	126	150	2.3	4.4	8.3	11	13	18
	8	68	1.2	4	148	5.1	16	108	126	152	2.2	4.8	8.9	11	13	19

※ HR: Heart rate (bpm), BLA: Blood lactate (mmol/L), RPE: Rating of perceived exertion
※ Load (kg): Low (25%max), Medium (35%max), High (45%max), MTF: Max.tethered force.

Fig.3-⑤ shows the EMGs during the ITS trials. The RMS values were computed using the EMGs of arbitrary 3 cycles (6 strokes of right and left) within the last 10 seconds at the first, fifth and the tenth session for each subject.

Fig.4 shows the shifts of the standardized integral values during the ITS trials. All the subjects showed the stabilizing tendency throughout. Also significant differences ($P<0.05$) were observed between the skill levels, even taking into consideration their tethered load.



Test muscles: M..Biceps brachii, M.Triceps brachii, M.Teres major, M.Trapezius

Figure 4. Changing in the total of standardized integral value of EMG during Interval tethered swimming

Fig.5 shows the result of statistical processing of muscle integral value standardization by ITS trials. Significant differences were found between skill levels, especially on M.triceps brachii, M.teres major, and M.trapezius. Also Significant differences observed between genders, especially on M.biceps brachii.

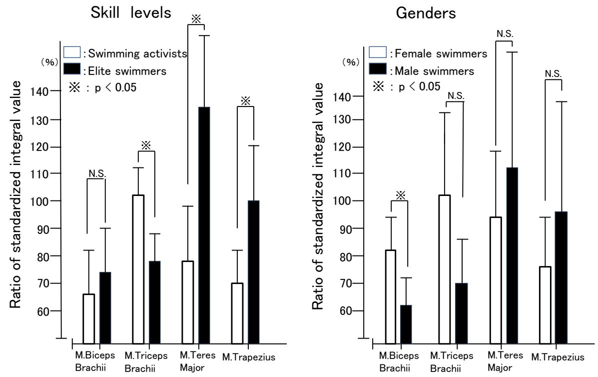


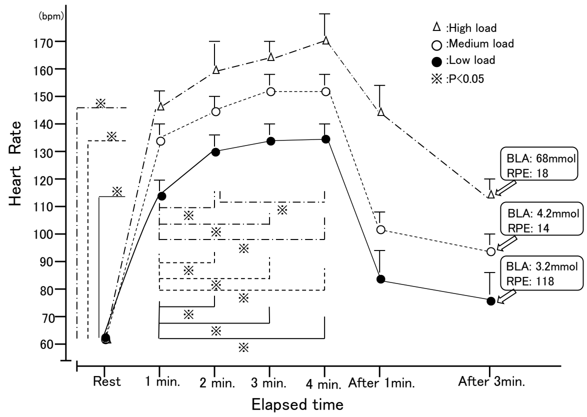
Figure 5. Significant differences by standardization of the integral value of EMG during Interval tethered swimming of two groups

3. 4 minutes Tethered Swimming (4TS)

For 4TS trials, each subject was given 3 kinds of tethered loads, 25%max (low), 35%max (medium) and 45%max (high). The results are shown in Table 2.

The HRs of the subjects were 104.4 ±11.2bpm at low load, 119.7±12.8bpm at medium load and 151.3±11.3bpm at high load. The BLAs were 3.6±1.6mmol/L at low load, 5.6±2.4mmol/L at medium load and 9.1± 2.5mmol/L at high load. The RPEs were 10.9± 1.8 at 25%max, 13.0± 1.1 at medium load and 15.9±2.3 at high load.

Fig.6 shows an example of the changes by load. At the loads of low level and medium level, no significant differences were shown chronologically after 2 minutes, confirming the stabilization.



HR: Heat rate, BLA: Blood lactic acid, Rating of Perceived Exertion

Figure 6. Changing in HR, BLA, RPE during /after 4min. tethered swimming

As shown in Fig.7, significant differences were found between low load and high load on HR, BLA and RPE for each trial, however no significant differences were found between low load and medium load as well as medium load and high load. The EMGs during the 4TS trials were shown in Fig.3- ⑥. As in the ITS trials, the RMS values were computed using arbitrary 3 cycles (6 strokes of right and left) within the last 10 seconds before completing a trial. The standardization of the RMS values for 4TS trial was calculated using the the RMS vales of the EMGs by FS trials as the control group.

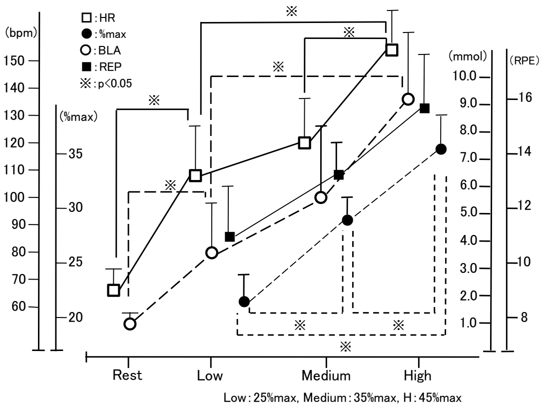


Figure 7. Physiological responses after 4min. tethered swimming

Fig.8 shows the results of statistical processing. Significant differences were found in the muscle activities of 4TS, in terms of loads, skill levels and genders. For skill levels, significant differences were found on M.biceps brachii and M.triceps brachii by medium loads and on M.teres major by high loads.For genders, significant differences were found on M.triceps brachii by high load, on M.teres major by all of the loads, and on M.trapezius by high load.

4. Resisted Swimming (RS) and Assisted Swimming (AS)

Fig.3- ②, ③ shows the EMGs during the RS and AS trials. On both modes, the EMGs of Fig.3- ① show similar muscle mechanism and electric discharge patterns as FS trials. However, the results of the standardization of integral values in Fig.9 show that significant differences were found between all of trial conditions on FS and RS, FS and MTS trials, as well as between AS and RS AS and MTS trials, while no significant differences were found between FS and AS.

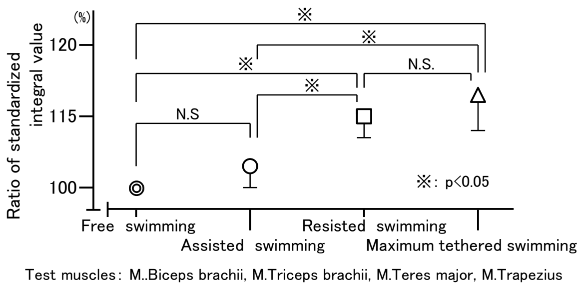


Figure 9. Comparison of standardized integral ratio of muscle of each tethered swimming for free swimming

As shown in Fig.10, significant differences were found in the integral values of all the muscles between FS and MTS trials. Significant difference was also found in the integral values of M.biceps brachii between FS and RS trials.

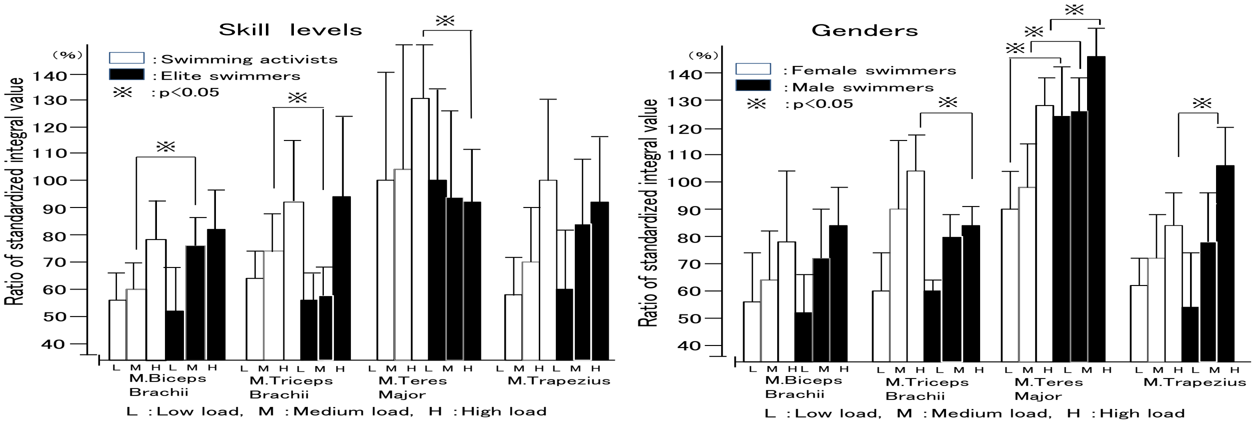


Figure 8. Significant differences by standardization of the integral value of EMG during 4min. Tethered swimming of two groups

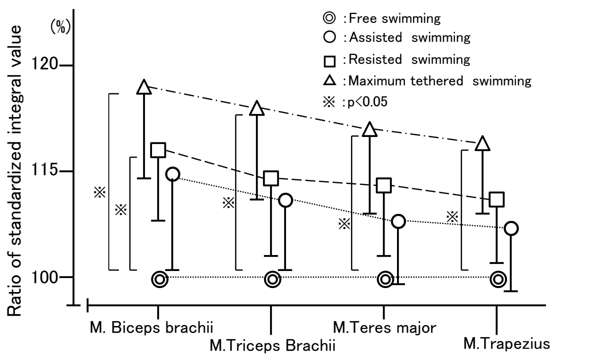


Figure 10. Comparison of each tethered swimming for free swimming

Ⅳ. Discussions

The present study was purposed to provide basic data with regard to set appropriate load and time for tethered swimming as a fitness training method, specifically, Interval tethered swimming, 4 minutes tethered swimming, resisted swimming and assisted swimming.

As for the ITS trials, all the subjects underwent the trials with the load of 45%max. As for the general tendency of all the subjects, no significant difference was found in the change of the HR. Looking into the detail of each session, there were significant differences shown between the first session and the third, however, from then on, it stabilized and showed no significant differences.

As shown in Fig.11, all the measurement parameters during ITS trials, such as HR, BLA and RPE showed the same level as the previous studies [15) 16) 17) 18)], suggesting the present trial was at the physical load level where improvement in aerobic endurance can be expected.

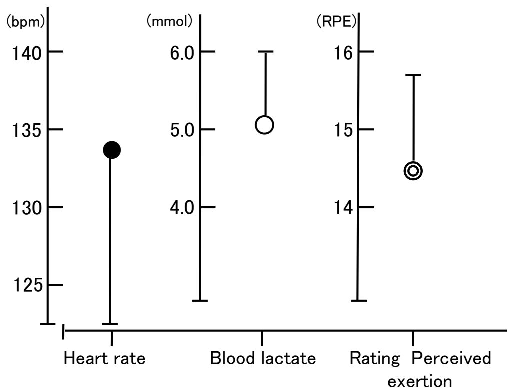


Figure 11. Physiological responses after interval tethered swimming

The result of EMG analysis during ITS trial showed no differences in muscle electric discharges or activity patterns at first, fifth and tenth sessions, supporting the premises that the 45%max ITS trial can be conducted without excessive muscle fatigue or affecting stroke mechanics.

As shown in Fig.5, the results of the EMGs analysis showed significant differences in skill levels on M.triceps brachii, M.teres major and M.trapezius and in genders on M.biceps brachii. This result suggests, though the relative load of 45%max was applied throughout, the difference of absolute muscle power between male and female were demonstrated in MTF trial, that in turn made the difference of the tethering load of each subject. It also demonstrated that the increase of load would have a great effect on M.triceps brachii, M.teres major and M.trapezius muscles. The result by skill levels showed significant difference especially on M.triceps brachii and M.teres major. M.triceps brachii and M.teres major were said to be the most relevant muscle in swimming propulsion [19)] and most frequently used muscle when pushing the water backward [20)] , and was thus considered the essential part in muscle training regimes for swimming. The result of the present study also shows more effective use of the muscle in the elite swimmer group.

From the stroke mechanics point of view, though a slightly stronger electric discharge was observed compared to FS trials. No large changes were observed in muscle activity mechanism, electric discharge time and patterns. And no significant differences were found in terms of SR and SL either. Combining these results, it appears that ITS trial would not affect stroke mechanics negatively. The study indicated that ITS trial with approximately 45%max load is useful as an endurance training without giving an undesirable effect on stroke mechanics.

As for the 4TS trials, 3 kinds of tethering loads, 25%max, 35%max and 45%max, were used for each subject. The physiological responses under each load are shown in Fig.7. HR, BLA and RPE showed desirable numbers for use in improving aerobic endurance.

As shown in Fig.6, all subjects demonstrated stabilization after 2 minutes at the loads of 25%max and 35%max, and especially at 35%max, very desirable value in improving aerobic endurance [18) 21) 22) 23)] was demonstrated. As shown in Fig.12 significant difference was found between 25%max and 45%max, however not between three kinds of load.

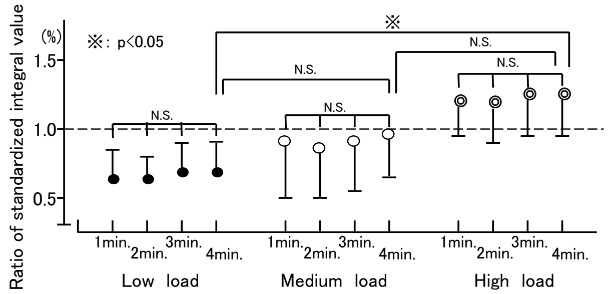


Figure 12. Comparison of standardized integral ratio between the different loads of 4min. tethered swimming

Fig.13 shows how tethering affects the OBLA-Load of a subject in the daily swimming activist group. The outcome matches the about 40%max (tethered load of approximately 4.7kg), that is the expected value for improving aerobic endurance.

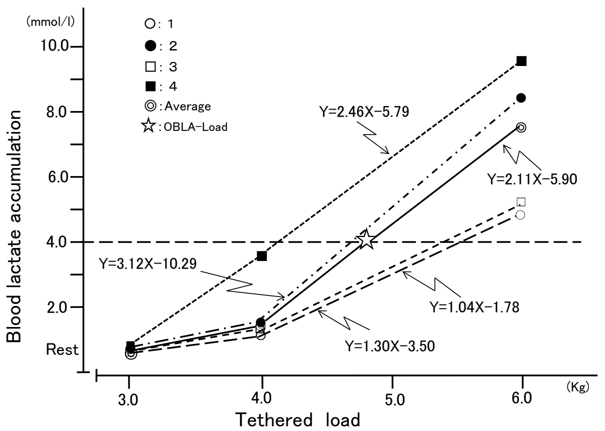


Figure 13. Changes in blood lactate accumulation after 4min. tethered swimming

As for the stroke mechanics, there were no significant differences found in terms of muscle activity mechanism and electric discharge pattern such as time and voltage. The stroke mechanics most similar to FS trial were observed between 35%max and 45%max. Significant differences were found in the RMS values in terms of tethered loads, skill levels and genders. It appears that the differences were caused by the difference in muscle outputs, such as the difference of absolute muscle power between male and female, as was found in ITS trials, as well as the difference of skill levels such as high-elbow position in water and in recovery.

These results as well as Y.Shibata [11)] indicated that 4TS trial with 35%max load does not negatively affect stroke mechanics and the physiological and psychological outcomes support the studies by Olbrecht J., et al.[23)] would be useful as a training method for competitive swimmers, and a fitness training methods for daily swimming activists as well.

Finally look at the EMGs for RS and AS trials. The RMS values are shown in Figs.9 and 10 respectively. The results of FS trial as the control group and MTS trials were also shown. Significant differences were found in all of muscles between the trials, as well as on M.biceps brachii between FS and RS trials. A similar tendency shown in the EMGs result in Fig.3 support the study by Maglischo, et al.[10)] in which they found that the SR in RS trial reduced more compared to AS trials. Also, the EMGs show some influence on stroke mechanics in RS and AS trials compared to FS trial. Considering the conclusions from previous studies, stating that AS improves stroke mechanics or RS is not helpful in improving velocity [10)], it was thought that AS is more desirable than RS. However, since the present study took swimming skill levels into consideration and used individual tethered loads for each subject, a slightly different conclusion can be drawn. That is, an appropriate exercise load can be established by setting an appropriate tethered load in tethered swimming and the stroke mechanics similar to FS trial can be maintained.

In any case, by the use of EMG analysis, exercises and motions that avoid injury became possible [24)], the judgment can be made whether muscle training for swimming is properly conducted [25)] as well as understanding whether the declining muscle activity pattern is due to muscle fatigue or intentional [26]. Taking these points into consideration, the present study clarified that tethered swimming with properly adjusted load is useful in fitness training, without giving excess physical load or negative influence on stroke mechanics.

Ⅴ. Conclusions

The present study aimed to provide basic data for the utilization of tethered swimming as a fitness (so-called endurance) training. The subjects, both elite competitive swimmers and daily swimming activists, were instructed to conduct MTS, ITS, 4TS, RS and AS trials with individually adjusted loads. Physiological and perceptual investigations were made with influence on stroke mechanics investigated. The findings appeared to warrant the following conclusions:

1) In ITS trial with approximately 45%max load, stabilization was observed both in terms of physiological and perceptual investigations without influencing stroke mechanics in both types of the subjects, suggesting that this mode of tethered swimming can be utilized as a fitness (so-called endurance) training for swimmers with a wide ranges of skill levels.
2) In 4TS trial, stabilization was observed after 2 minutes in 25%maxand 35%max loads for both types of the subjects. Stabilization was also achieved, physiologically and perceptually, at 35%max without showing any negative affect on stroke mechanics, suggesting that this mode of tethered swimming can be utilized as a fitness (so-called endurance) training for swimmers in many levels.
3) More active discharge patterns and electrical potentials were observed in RS and MTS trials compared to FS trial while similar discharge patterns and electrical potentials of FS trial were observed in AS trial. That suggests that RS can be used as a fitness (so-called endurance) training if appropriate loads are set.

The tethered swimming methods shown in the present study can be used as a fitness (so-called endurance) training for competitive swimmers by establishing appropriate exercise loads, without giving a negative influence on stroke mechanics. It can also be used for daily swimming activists for fitness regimes by establishing the appropriate load in the same way. As for the application of RS, attention should be given for its excessive use in competitive swimmers, and for daily swimming activists, it should be avoided altogether.

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