Suspended Push-up Training Augments Size of not only Upper Limb but also Abdominal Muscles

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ABSTRACT

We investigated the effects of sling-based, suspended push-up training on muscle size and function of upper limb and abdominal muscles. Eight men conducted suspended push-ups to failure 3 sets/session, 3 sessions/week, for 8 weeks. The maximum number of push-ups during training gradually and from the first to last training session (+92 %), suggesting improved muscle endurance. After the training, muscle thickness of the elbow extensors (+16 %) and flexors (+3 %), as well as abdominal muscles (rectus abdominis: RA, +27 %; external oblique: EO, +14 %) significantly increased. No changes occurred in maximum isometric strength of elbow extension or flexion, nor in 1-repetition maximum bench press. In a follow-up experiment, electromyograms (EMGs) of RA, EO and internal oblique (IO) during suspended push-ups to failure were measured and normalized to those during maximum voluntary contraction of each muscle (% EMGmvc) in six men. EMG significantly increased when reaching failure in all muscles (RA: 46–88 %, EO: 32–50 %, IO: 19–52 %, start-end), and was particularly high in RA. These results suggest that suspended push-up training can augment size of not only upper limb but also abdominal muscles, likely attributable to high muscle activities during exercise; however, this does not necessarily improve maximum strength after training thus warrants careful interpretation/application.

Introduction

Training of the trunk musculature, the abdominal muscles, in particular, has become an essential facet of many training programs [1]. The main reason behind this is that greater trunk stability is suggested to benefit athletic performance by providing a foundation for greater force/power production in the limbs [2]. For this purpose, instability resistance exercise using unstable surfaces and devices [1–3] has been increasingly implemented, because this type of exercise is known to induce greater muscle activity (i. e. training stimulus) in trunk muscles compared to normal (stable) exercises due to increased demands of stabilization [4–6].

Sling exercise is one of the most frequently implemented and studied instability resistance exercises [4–10], and has been shown to be effective in improving muscle function [5, 7, 8, 10]. For example, Dannelly et al. [7] demonstrated that a combination of 10 types of sling exercise training (e. g. suspended push-up) in untrained females was equally as effective as traditional resistance training for increasing strength [e. g. one-repetition maximum (1RM) bench press]. It is also reported that throwing velocity in female athletes (handballers and softballers) was significantly increased after a combination of 5–9 types of sling exercise training [9, 10] but not after their traditional resistance training analogs [9] or regular (sport-specific) training [10]. A recent study by Lima et al. [8] examined the effect of suspended push-up training performed alone (without other sling exercises) on muscle function, showing superior improvements over stable push-up training for muscle (push-up) endurance and chest press strength. These results collaboratively support the efficacy of sling exercise training.

While the above findings are all important, what is lacking to date is the key information regarding the putative effect of instability resistance exercise; does it actually train the trunk, or in particular, abdominal muscles? Although some studies cited above reported gains in chest press strength [8] or 1-RM bench press [7] after sling exercise training, which may be partly attributable to enhanced function of trunk including abdominal muscles, no convincing evidence exists supporting this theory. Examining changes in size of abdominal muscles can shed light on whether these muscles are actually trained by instability resistance training, which would be of great interest to many training/rehabilitation practitioners and researchers. Furthermore, clarifying the effect of instability resistance training on size and strength of the limb muscle that was mainly involved in the exercise (e. g. the elbow extensors in suspended push-ups) would be also useful in identifying mechanisms underpinning a potential performance improvement, which has also never been examined.

The main purpose of this study therefore was to investigate the effect of sling exercise training on size and function of abdominal and upper limb muscles (Experiment 1). To this end, we designed 8-week suspended push-up training. This exercise was chosen because it was performed in all of the previous studies that conducted sling exercise training cited above [5, 7, 8, 10], and can be considered as the representative sling exercise. Additionally, we assessed muscle activity levels of abdominal muscles via electromyogram (EMG) during the exercise to provide information regarding exercise intensity for these muscles (Experiment 2). We hypothesized that 1) 8-week suspended push-up training would increase size of not only upper limb but also abdominal muscles, and 2) activity levels of abdominal muscles during the exercise would be sufficient to induce hypertrophy (e. g. > 40 % of maximum activation [11]).

Materials and Methods

Experimental design

The sample size for Experiment 1 was calculated on the basis of an α-level of 0.05, a power (1 − β) of 0.80, and a 20 % change (effect size = 1.2) in muscle thickness of an abdominal muscle after 8-week abdominal bracing training [12]. This revealed that eight participants would be needed to detect a significant change in muscle thickness (G * Power; Heinrich- Heine-Universität Dusseldorf, Dusseldorf, Germany). For Experiment 2, the sample size was not calculated because it was a follow-up experiment, the purpose of which was to provide supportive information regarding exercise intensity. Eight and another (different) six healthy male university students majoring in physical education participated in Experiment 1 and 2, respectively. The means and SDs of their age, body height and body mass were 22.1 ± 3.8 years, 168.5 ± 4.7 cm, and 66.2 ± 8.1 kg for Experiment 1, and 21.2 ± 3.8 years, 1.71 ± 0.02 m, and 65.4 ± 3.2 kg for Experiment 2, respectively. All participants were required to be healthy (based on a university medical checkup) males aged 18–35, with no history of systematic (≥ 30 min/day, ≥ 2 days/week) resistance training program, and no major (potentially influential) injuries before the study intervention. No injuries and/or dropouts occurred through this study. Participants visited the laboratory and were fully informed about the purpose, procedures and possible risks involved in the study, and provided written informed consent. All participants experienced and were familiarized with the suspended push-ups and other tasks involved in testing before data collection. This study was approved by the local ethics committee, and was conducted in accordance with the ethical standards of the IJSM [13].

Experiment 1: Training intervention

Training program

Suspended push-up training was conducted 3 sets/session, 3 sessions/week, for 8 weeks by using a Redcord Trainer (Kilsund, Norway). In a prone position with the shoulders abducted at 90 ° and elbows fully extended (~0 °), participants grasped the grips with both hands at the width slightly (plus one palm for each side) wider than the shoulder-width. The toes were placed shoulder-width apart on a wood base so that the height of the hands and toes were horizontal. The pelvis was raised off the floor with the body weight distributed on the hands and toes [6], and participants repeated push-ups to failure at a rate of 45 per minute based on a metronome. Participants were instructed to keep the trunk straight during the whole movement and lower the body until the elbow was flexed at 90 °, and then return to the original position. The exercise was discontinued when participants could no longer keep up with the tempo. 2-min rest intervals were taken in between sets. A rest period of 2–3 days (~48–72 h) were taken between sessions. Number of push-ups (repetitions) performed per set was recorded throughout all training sessions, and maximum number of repetitions (REPmax) for each session, which was always observed in the first set, was reported as an index of muscle endurance.

Measurements

Before and after the training intervention, indices of muscle size and function were measured. Rest periods of 1–2 days and 2–3 days were taken between the pre-test and first training session and between the final training session and post-test, respectively. All measurements were conducted on the right side of the body, and the following variables were obtained:

Muscle thickness B-mode ultrasound apparatus (Prosound 2; Aloka, Tokyo, Japan) was used to measure muscle thickness of the elbow extensors (EEs), elbow flexors (EFs), rectus abdominis (RA), external oblique (EO) and internal oblique (IO) at rest by the same procedure used in previous studies [12, 14–16]. Briefly, muscle thickness of the upper arm muscles was measured at 60 % of the distance down from the acromial process to the lateral epicondyle of the humerus, and included the long and medial heads of the triceps brachii for the EEs, and the biceps brachii and brachialis for the EFs. For the abdominal muscles, muscle thickness was measured at a position 2–3 cm to the right of the umbilicus for the RA, and at midway between the iliac crest and the costal margin, which was adjusted to ensure that the fascial borders appeared parallel on the screen, for the EO and IO. All the measurements were done by the same researcher.

Maximum isometric strength Torque during isometric maximum voluntary contraction (MVC) of EEs and EFs was measured using an isokinetic dynamometer (Biodex system2; Biodex Medical Systems, NY, USA). Participants were seated in an adjustable chair with support for the back, elbow, shoulders and hips. The shoulder joint was flexed so that the upper arm was horizontal to the ground. The upper arm tested was supported by an arm pad, and the dynamometer was rotated 30 ° outward from the chair. During the torque measurements, the hips and back were held tightly to the seat with adjustable lap belts, and the upper arm was fastened with a strap belt to the arm pad. With the elbow joint angle at 90 ° and the wrist in a neutral position, following a sufficient warm-up period, two MVCs for each of EEs and EFs were performed with a rest period of 3 min between trials. Subsequent trials were performed, if the differences in the peak torques of the two MVCs for each muscle group were more than 5 %. The trial with the highest peak torque was adopted as the maximum torque for each of the EEs and EFs.

1-RM bench press The 1-RM bench press was measured with a commercially available standard bench press system (Hammer Strength, Life Fitness, Rosemont, USA). As a warm-up, participants performed the bench press several times with a load of 50 % and then 75 % of their assumed 1-RM. Subsequently, 1.25–2.5 kg weight plates for each side were gradually added with at least 2-min intervals between trials, and the maximum load lifted was determined as 1-RM. During the testing, the feet and hips were kept on the floor and the bench, respectively.

Experiment 2: Abdominal muscle activity during suspended push-ups

EMG during suspended push-ups and normalization

To estimate muscle activity levels during the suspended push-ups, EMGs were measured from the RA, EO and IO during the push-ups, as well as during isometric MVCs for these muscles for the purpose of normalization (i. e. % of maximum activation). EMG amplitude has a large within and between-subject variability in general due to various factors such as differences in muscle and subcutaneous fat thickness among others, but this can be minimized, albeit not fully removed, by the above normalization [17]. Although it would be ideal, if we could also estimate muscle activity levels for the other key muscles of the push-ups (e. g. the pectoralis major or triceps brachii), joint angles and therefore muscle lengths of these muscles largely change during dynamic push-ups, which makes EMG normalization and interpretation of the data difficult [17]. Thus, we only recorded EMGs from the abdominal muscles, the lengths of which were kept constant during both the push-up and MVC tasks.

Electrode locations were 3-cm lateral to the umbilicus for the RA, halfway between the crest of the anterior superior iliac spine and the lower edge of ribs above the anterior super iliac spine for the EO, below the EO electrodes and superior to the inguinal ligament for the IO [12, 18]. After preparation for reducing the skin impedance, Ag/AgCl surface electrodes (diameter: 8 mm) with 2-cm inter-electrode spacing were placed parallel to the assumed muscle fiber orientations, and were connected to a differential amplifier (gain: × 1 000, common-mode rejection ratio: > 80 dB, input impedance: > 100 MΩ; MEG-6100, Nihon Koden, Japan) [12, 18]. The EMG signals were obtained at a sampling rate of 2000 Hz using a 16-bit A/D converter (PowerLab 16/35, ADInstruments, Australia) and stored on a personal computer. After a warm-up with submaximal contractions for each task, participants performed trunk flexion, trunk rotation and lateral flexion against manual resistance with maximal effort for 5 sec, twice for each task with a rest period of 2 min, in accordance with previous studies [12, 16, 18, 19]. Then, after a rest period of > 10 min, participants performed suspended push-ups to failure using the same sling system as for Experiment 1. In off-line analysis, EMG root-mean square (RMS) values were calculated for a middle 3-sec window during all MVCs, and the highest value obtained regardless of the MVC tasks was adopted as EMGmvc for each muscle. RMS values during the push-ups from the start to the end (failure) were calculated at 10 % time intervals based on the time/repetition of REPmax for each participant (i. e. 10 %, 20 % and up to 100 % REPmax; 10 time points), and normalized to those during MVCs (i. e. % EMGmvc) for each muscle to examine changes in muscle activity levels during the push-ups to failure.

Statistical analysis

Descriptive data are presented as means ± SDs. For Experiment 1, a one-way repeated ANOVA with a Tukey post hoc test was used to examine the changes in REPmax among all (24) training sessions. A paired student's t-test was used to compare the change between the pre- and post-test in muscle thickness and strength variables. For Experiment 2, a repeated two-way ANOVA with a Tukey post hoc test was used to examine the changes in muscle activity level over time during the push-ups to failure (3 muscles × 10 time points). Statistical significance was set at $P < 0.05$. As an index of the effect size, Cohen's d values were reported with P values, and interpreted as < 0.20 trivial, 0.20–0.49 small, 0.50–0.79 medium and ≥ 0.80 large. All data were analyzed using SPSS software (SPSS Statistics 20; IBM, New York, USA).

Results

REPmax of push-ups in training

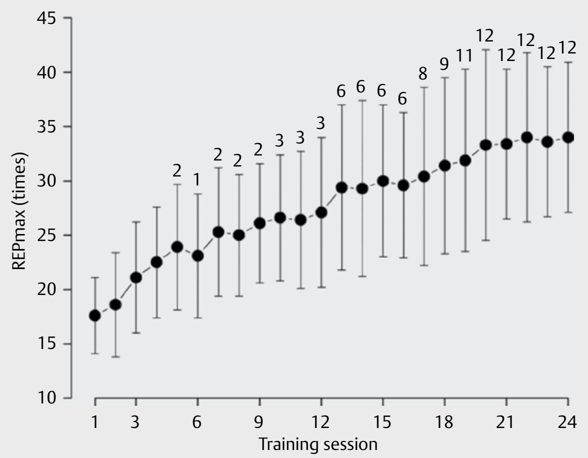
▶ **Fig. 1** shows changes in REPmax of push-ups through all training sessions. Significant increases from the session 1 were found at the session 5 and thereafter ($P \leq 0.002$, d = 1.17–3.01). Significant differences were also found at the middle-late phase of the training period compared to the earlier sessions, indicating that REPmax kept increasing during the training intervention.

Training-induced changes in muscle size and strength

The 8-week suspended push-up training induced significant increases in muscle thickness of the EEs (+ 16 %, P = 0.015, d = 1.44), EFs (+ 3 %, P = 0.034, d = 0.34), as well as RA (+ 27 %, P = 0.002, d = 2.42) and EO (+ 14 %, P = 0.040, d = 0.88) (▶ **Fig. 2**), but not IO (pre vs. post, 12.9 ± 2.0 vs. 13.3 ± 2.8 mm, P = 0.320, d = 0.17). No changes occurred in any of the isometric maximum strength values for elbow extension (24.6 ± 6.3 vs. 26.8 ± 7.8 Nm, P = 0.466, d = 0.30) or elbow flexion (53.7 ± 8.9 vs. 52.9 ± 5.1 Nm, P = 0.678, d = 0.12), nor in the 1-RM bench press (71.3 ± 12.8 vs. 72.8 ± 11.1 kg, P = 0.420, d = 0.13).

Muscle activity level during suspended push-ups

▶ **Fig. 3** shows changes in muscle activity level of the abdominal muscles during push-ups to failure. A two-way ANOVA found a significant time * muscle interaction ($P \leq 0.001$). A Tukey post hoc test revealed significant increases for all muscles as reaching failure (≥ 80 % of REPmax) compared to earlier time points ($P \leq 0.048$, d = 0.52–1.60).

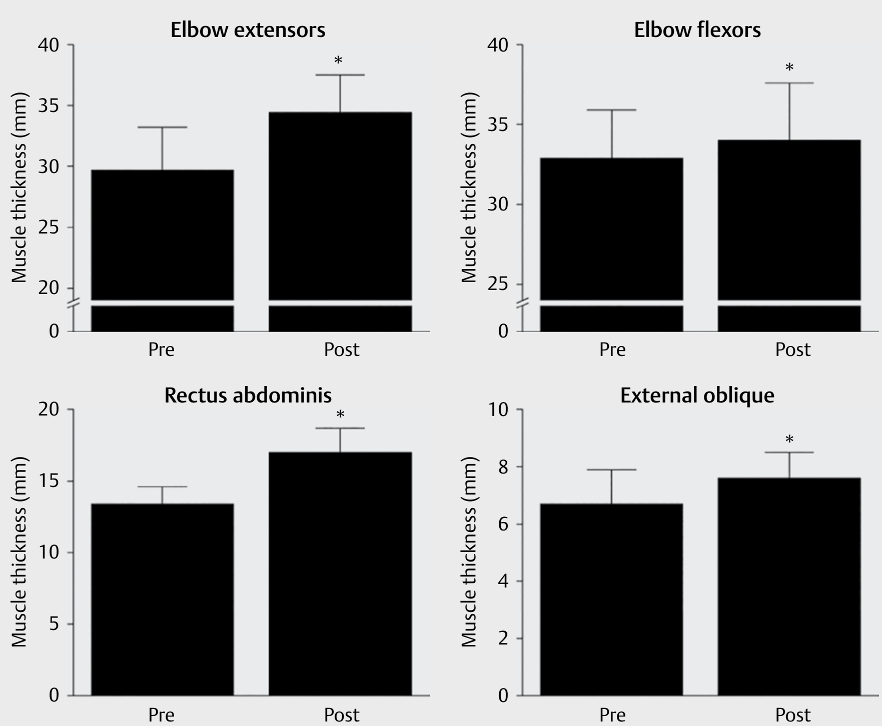


▶ **Fig. 1** Changes in maximum number of push-up repetitions (REPmax) through training sessions. Values are means ± SDs. The numbers above symbols indicate a significant difference (increase) compared to the described number of session and earlier sessions at $P<0.05$. For example, the number "12" at the training session 24 indicates that REPmax at the session 24 was significantly higher than those at the sessions 1–12.

Discussion

The primary findings obtained here were that the 8-week suspended push-up training increased size of not only the upper arm but also the abdominal muscles, and EMG data indicated that activity levels of the abdominal muscles during exercise were sufficient to induce hypertrophy (at least in RA and EO, explained below). On the other hand, no changes occurred in maximum isometric strength of elbow extension or flexion, nor in 1-RM bench press. These results suggest that suspended push-up training can augment size of not only upper arm but also abdominal muscles, but this does not necessarily increase maximum strength after training, which warrants careful interpretation of the results and its application.

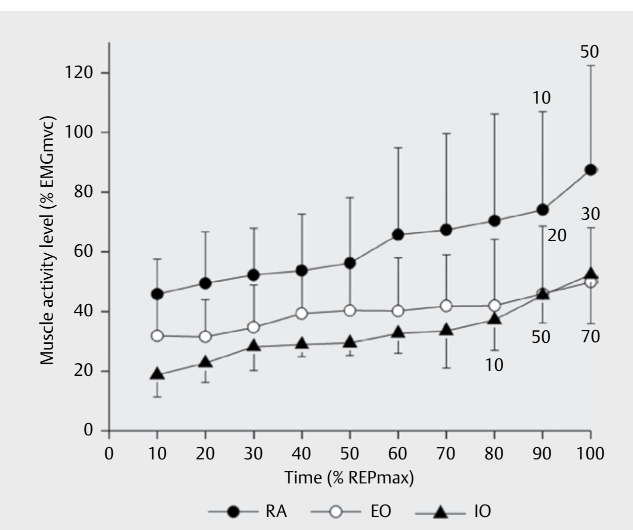
Muscle thickness significantly increased in the upper arm and abdominal muscles after training (▶ **Fig. 2**). To the authors' knowledge, this study is the first to document muscle hypertrophy of abdominal or any other muscles after instability resistance training. These results support our hypothesis. The hypertrophy of the EEs (+16 %) is not surprising given that this muscle group works as an agonist during push-ups where repeated elbow extensions are performed. What is somewhat surprising is the hypertrophy of the EFs, albeit in a much smaller degree (+3 %), because this muscle group works as an antagonist during push-ups. This is most likely attributable to the agonist-antagonist co-contractions, which allow for stiffening of joints to control the position of the limb and to per-



▶ **Fig. 2** Changes in muscle thickness pre- and post-training. Values are means ± SDs. An asterisk indicates a significant difference from pre at $P<0.05$.

form the task accurately [1, 6]. Although we do not have any data regarding muscle activity levels (i. e. exercise intensity) for these muscles during push-ups, due to the aforementioned reason for the complexity of EMG normalization, it appears that muscle activity levels were sufficient for the agonist EEs and even antagonist EFs to induce hypertrophy. It is worth mentioning that 12 % increase in muscle thickness of the EEs, but not EFs, was reported after 9 weeks of traditional bench press training (75 % 1RM, 10 reps/set, 3 sets/session, 3 sessions/week) in untrained men [20]. Collectively, these results suggest that suspended push-up training can induce similar or greater hypertrophy in the EEs compared to traditional bench press training, and hypertrophy of the EFs is likely specific to the suspended push-up training.

What is further remarkable here is the fact that the size of abdominal muscles significantly increased after training to a similar and even greater extent for the EO (+14 %) and RA (+27 %), respectively, compared to the EEs (+16 %). These changes were much greater than the inter-day coefficient of variation for this measurement we have previously found [EO: 3.7 %, RA: 0.8 %, EEs: 1.4 % (12, 15)], and the effect sizes of the changes in these muscles were all large (0.88–2.42). Thus, we are confident that the observed changes are not measurement errors but actual muscle hypertrophy. Muscle activity levels (% EMGmvc values) for the RA, EO and IO were 46, 32 and 19 %, respectively, at the start of the exercise, and all gradually increased over time and were 88, 50 and 52 % at the end (▶ **Fig. 3**). Such increases in muscle activities during sustained or repeated submaximal contractions [21], as well as significant muscle hypertrophy after training [22], when performed to failure have been well reported and are considered to be mainly due to additional (near maximal, e. g. RA) motor unit recruitment induced by fatigue. On average over time, muscle activity levels during the suspended push-ups were 62, 40 and 33 % for the RA, EO and IO, respectively, and these values correspond well with the degree of observed hypertrophy after training. Interestingly, in terms of no significant hypertrophy in IO, this also agrees with the classic suggestion by Hettinger [11] that a minimum intensity of ~40 % is required to increase muscle size/strength by resistance training. Caution is needed, however, when interpreting the results on the changes (and averaged values) in EMG, as EMG amplitude during MVC (a denominator in the normalization calculation) may have changed through and after the fatiguing push-ups, which we did not measure. Thus, more precise information remains to be examined in future studies to better understand the association between muscle activity during exercise and training outcomes. Nevertheless, our results on training-induced changes in muscle size and EMG during exercise strongly indicate that suspended push-ups can train superficial abdominal muscles, particularly the RA which mainly controls the straightened trunk position during the exercise.



▶ **Fig. 3** Changes in muscle activity level during suspended push-ups to failure. Values are means ± SDs. The numbers above or below symbols indicate a significant difference (increase) compared to the described number of time point and earlier time points for the same muscle at P < 0.05. For example, the number "50" at the time point of 100 % for the RA indicates that muscle activity level of the RA at the time point of 100 % was significantly higher than those at the time points of 10–50 % of the RA.

REPmax gradually and significantly increased as the training progressed (▶ **Fig. 1**), with an increase of 92 % at the final compared to the first training session. This is well in line with Lima et al. [8] who found REPmax to increase by 82 % after 8 weeks of suspended push-up training performed to failure (1–3 sets/session, 2 sessions/ week). The increase in REPmax would be due to an improvement in muscle endurance and/or coordination, but mainly the former because the participants were well familiarized with the task before starting the training and REPmax kept increasing throughout the training period (▶ **Fig. 1**). On the other hand, no changes were found in any of the isometric elbow extension/flexion strength and 1-RM bench press, despite the significant hypertrophy of the upper limb and abdominal muscles. This is a seemingly counterintuitive result but may be explained by the concept of "training or task-specificity," where a training-induced performance improvement is most clearly observed in testing tasks similar to the training task [23–26]. For example, it has been shown that leg press [24] or squat [26] training significantly increased respective 1-RM, as well as muscle size of the quadriceps femoris, but no change was found in isometric knee extension strength. This concept would at least partly explain the large improvement in REPmax and lack of improvement in strength variables, respectively, after the suspended push-up training. In other words, suspended push-up training performed to failure can increase muscle size and task-related muscle function such as muscle (push-up) endurance, but its effects on maximum strength under a normal (stable) condition is negligible. At the same time, these results highlight the importance of carefully selecting training tasks based on a specific training goal.

In light of these considerations, how can or should we apply the current findings to practical settings? The results clearly demonstrated that the upper limb and superficial abdominal muscles can be simultaneously trained by suspended push-ups. It is worth noting that the changes in the size of abdominal muscles (+ 14–28 %) in this study were comparable to those (+ 4–28 %) induced by training programs that specifically targeted the abdominal muscles in previous studies [12, 27]. Furthermore. this study found a large improvement in push-up endurance (+92 %), which is likely superior to the effect of non-suspended push-up training [8] (discussed below). Thus, the direct interpretation is that the suspended push-up is a time-efficient training modality that can simultaneously and effectively train not only the push-up-specific but also abdominal muscles. On the other hand, as discussed above, if one's training goal is focused on or includes enhancing maximum strength such as 1-RM bench press, the current results indicate that it would be necessary to perform the target task, and possibly some training stimulus variations can be made by implementing suspended push-ups in the training program. From a practical perspective, it is interesting to explore the best combination of training protocols incorporating suspended push-ups, bench press and/or non-suspended push-ups (also see below) to achieve the best training outcomes.

We did not set a training group conducting conventional non-suspended push-up training. Thus, it is unknown whether or how much the observed changes would differ from such a conventional training regimen. To the authors' knowledge, no study has investigated the effect of non-suspended push-up training on abdominal muscle size. With the same EMG technique used in this study, we [6] reported that the activation levels of the RA, EO and IO during suspended push-ups (not performed to failure) were all significantly greater than those during non-suspended push-ups (RA: +37 %, EO: +21 %, IO: +32 %). Based on this, potential effect of non-suspended push-up training on abdominal muscle size would likely be less, if any, than suspended push-up training, although this needs to be experimentally confirmed in a future study. Regarding changes in muscle function, on the other hand, Lima et al. [8] compared the effects of suspended vs. non-suspended push-up training, and found superior improvements for the suspended over non-suspended training in improving push-up endurance and isometric chest press strength. Their training program was quite similar to ours; exercise was performed to failure, 1–3 sets/session, 2 sessions/week, for 8 weeks. The main difference between their study and ours seemingly is that they altered the suspension configuration and push-up height through their training program, while we kept them constant. Taken together, it is possible that the suspended push-up training, with manipulations of training stimuli (e. g. suspension configuration and push-up height) through training intervention, may induce superior improvements in muscle size and task related-strength over non-suspended training. Further research is warranted to substantiate these issues, using various types of exercises including, but not limited to, suspended push-ups in order to clarify the effect of sling-based training.

In conclusion, the 8-week suspended push-up training increased size of not only upper arm but also abdominal muscles. Activity levels of abdominal muscles during exercise gradually and significantly increased in all muscles; they were relatively high for RA and EO, and corresponded to the degree of their hypertrophy after training. Although REPmax during suspended push-ups largely increased through training, there were no changes in maximum isometric strength of elbow extension/flexion or 1-RM bench press tested under normal (stable) conditions, which would be likely explained by the task-specificity. These results suggest that suspended push-up training can augment the size of not only upper arm but also abdominal muscles, but this training does not necessarily increase maximum strength, which warrants careful interpretation of the results and its application. Finally, it should be noted that the participants in this study were all physically active young males, and therefore the findings cannot be generalized to the broader community based on this study alone. More studies are needed to establish goal-oriented guidelines for sling exercise that are applicable to a wide spectrum of individuals.

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Conflict of Interest

Authors declare that they have no conflict of interest.

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