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THE EFFECT OF AN ABDOMINAL MUSCLE TRAINING PROGRAM ON INTRA-ABDOMINAL PRESSURE

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ABSTRACT. The effect of 10 weeks' specific abdominal strength training (resisted trunk rotations) on intra-abdominal pressure was investigated in 10 healthy males. Isometric rotational force, trunk flexor and extensor torque and intra-abdominal pressure were measured as well as intra-abdominal pressure responses to Valsalva manoeuvres, maximal pulsed pressures, drop jumps and trunk perturbations. The rotational strength increased 29.7% after training without significant change in intra-abdominal pressure. The isometric flexor strength did not change, while the extensor strength increased 11.0%. Valsalva and pulsed pressures increased 11.6 and 9.2%, respectively. The rate of intra-abdominal pressure development during pulsed pressures, drop jumps and trunk perturbations increased after training. The level of intra-abdominal pressure during the latter two tasks remained unchanged. It is concluded that an increase in strength of the trunk rotators with training improves the ability to generate higher levels of voluntarily induced intra-abdominal pressure and increases the rate of intra-abdominal pressure development during functional situations.

Key words: abdominal muscle training, intra-abdominal pressure, Valsalva, G-tolerance.

INTRODUCTION

The development of an increased intra-abdominal pressure (IAP) has been discussed since the mid 1950s as a mechanism for reducing forces on the spine and thereby minimising injury. This premise has led to many studies where external forces, muscle activities and IAP have been directly measured or theoretically calculated to determine the net force acting upon the spinal column during trunk loading (4, 6, 20). Several studies have concentrated on determining these parameters during lifting tasks and have found substantial increases in IAP with increases in lifting load. Recently, IAP responses during controlled postural tasks (9, 12) and while perturbing the trunk to disturb balance (10) have also been investigated. These studies have shown that during most involuntary trunk movements, increases in activity of specific muscles of the ventro-lateral abdominal wall (primarily transversus abdominis) and an associated elevation of IAP occur. This IAP increase has been interpreted as a mechanism to help stabilise the trunk and restore balance. During voluntary tasks, pre-activation of these same abdominal muscles often occurs as a strategy to help secure the trunk for the oncoming disturbance (10, 17). The rate at which the IAP increase can be achieved is likely to have additional functional consequences.

The idea of enhancing the IAP response for improved spinal unloading and trunk stability has been suggested earlier, and abdominal muscle strength training studies have therefore been undertaken in an effort to determine if abdominal strength gains can directly influence the development of IAP (5, 13, 14, 15). Isometric and dynamic sit-up exercises have been the most common form of training (13, 14, 15). Generally, no significant increases in IAP have occurred in these studies despite significant increases in trunk flexor strength. However, one study has reported individual cases in whom there was a substantial increase in IAP (5). Most of the above mentioned studies have measured IAP while performing abdominal strength measurements or sub-maximal lifts and not during other functional tasks. Only one study has measured maximal voluntary abdominal pressurisations and the non-significant increase in this measure was clouded by the possibility that the training group were 'well trained' as a result of their occupation prior to the training (5).

The common use of sit-ups as the training stimulus to increase IAP is questionable, as this form of abdominal exercise is known to predominantly acti-

Table I. *Mean age, body mass and height of the training and matched control groups*

Subjects	Age (years)	Body mass (kg)	Height (m)
Test group	26 (SD 3)	79 (SD 5)	1.81 (SD 0.02)
Control group	26 (SD 3)	77 (SD 5)	1.80 (SD 0.01)

vate and train the rectus abdominis muscle (2, 16) a muscle whose fibres primarily generate trunk flexor torque (7). Anatomically the transversus abdominis, obliquus internus and obliquus externus are the three muscles of the ventro-lateral abdominal wall which have the greatest potential to increase IAP. Recent studies using intra-muscular electromyographic recordings have substantiated this rationale (8, 9, 10). It was observed that activation of these three muscles (but principally transversus abdominis) and not rectus abdominis was correlated to the increases in IAP. In addition, these muscles were active while performing both standing and sitting loaded trunk rotations (cf. 8, 9, 10). It therefore seems appropriate to direct training toward the trunk rotators, and not the primary trunk flexors, if the outcome is to improve the rate and the magnitude of IAP increase during loaded tasks.

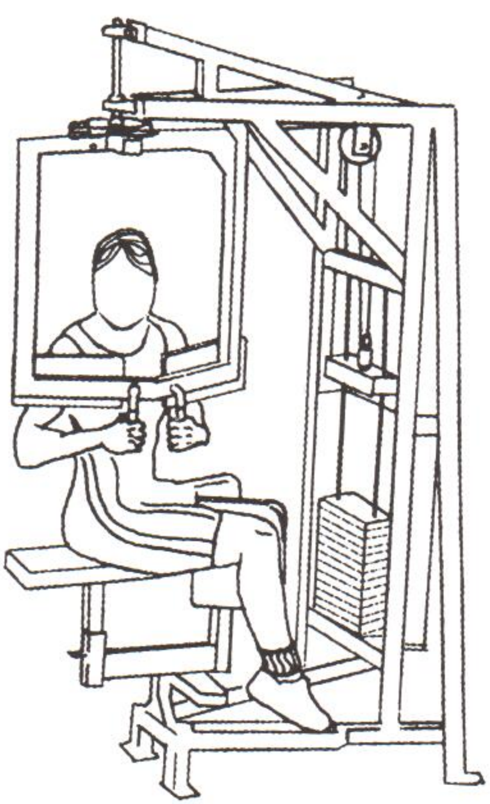

Fig. 1. The trunk rotation training machine ("Torso Trainer") used for the dynamic abdominal training program.

The present study was designed to investigate the effect on IAP of an abdominal strength training program consisting of trunk rotations aimed at stimulating a strength increase in the muscles specifically involved in the control of IAP. The functional consequence of any change in IAP with training was examined under a variety of voluntary and involuntary loading situations.

MATERIALS AND METHODS

Subjects

Fifteen male subjects participated in the study with 10 and 5 subjects allocated to a training and a control group, respectively. The mean age, body mass and height of the training and the matched control groups are shown in Table I. All subjects were healthy physical education students attending the same classes. None of the subjects were involved in abdominal muscle training outside their normal class activity.

Training regime

Trunk rotation strength training was performed dynamically using a specialised trunk rotation training machine (Fig. 1; Cybex Torxo Trainer; Lumex Inc., USA). Training consisted of three training sessions a week for 10 weeks. Each training session was interspaced by at least one day of rest. Three sets of 10 repetitions in both directions (90° of trunk rotation about the longitudinal axis to each side) resulted in a total of 60 repetitions per training session. The timing was predetermined by an auditory metronome with the initial inward movement (concentric muscle action) and the resisted outward return (eccentric muscle action) taking one second to perform, respectively. One minute of rest was given between each set. The level of loading was set at 80% of what could be achieved maximally in a one-repetition trial. This one-repetition level was adjusted weekly for any change in strength.

A battery of tests (see below) was given to the training and control groups prior to, mid-way and at completion of the training program.

IAP measurement

In all tests, IAP was measured from within the gastric ventricle using a micro-tip pressure sensitive transducer (Millar Micro-tip, PC 340, Millar Instr., USA) as described in earlier studies (11, 12). The depth of insertion was determined by external measurement, from the subject's nose to just below the xiphoid process, and the catheter marked accordingly. Introduction of the transducer was done after the administration of an anaesthetic spray (Xylocain 10%) to the nasal passage. To ascertain that the catheter was below the diaphragm and within the abdominal cavity, a series of respiratory and abdominal manoeuvres was performed with the glottis open. The catheter was deemed to be in place when on rapid deep inspiration and during forceful isometric contraction of the abdominal muscles the pressure signal showed a sharp positive increase. The catheter was then securely fastened to the skin.

Tests

Trunk rotation strength. Rotational trunk strength was measured isometrically using the 'Torso Trainer' which had been modified to function statically at a position of 45° from centre about the longitudinal axis. A maximal isometric contraction was performed for 3 seconds while trying to return the trunk and machine to centre (0°). Force was measured by a load cell (Bofors KRG-4, load range 0–2 kN; Nobel Elektronik, Sweden) which was placed in series with the cable affording the static resistance. Peak isometric force was considered to be the mean of a one-half second period of nearly constant maximal force production. Peak IAP was determined as the mean value for the same period. Three trials were achieved in each direction in a randomised order. In addition, three trials to each side were performed at 50% of peak isometric force with the use of visual feed-back of the force signal. These additional six trials were also randomised for direction.

Trunk flexion and extension strength. Maximal voluntary isometric trunk flexion and extension strength was measured using a swivel table (11, 21) attached to a dynamometer (Cybex II, Lumex Inc., USA). Subjects were positioned on their side in a straight body position (0°) with the L3 vertebra aligned over the axis of the table and the dynamometer. Securing straps were placed about the trunk (T7 level) pelvis and shanks. Three maximal isometric trunk flexions and three maximal isometric trunk extensions were performed in a randomised order. Peak flexor and extensor torque (taken as the mean of a one-half second period of nearly constant maximal force production) and peak IAP (the mean over the same period as the force measurement) were recorded for each trial.

Voluntary pressurisations. To determine each subject's capacity to voluntarily maximise IAP, a series of Valsalva manoeuvres, each held for 3 seconds, was performed while standing. Peak IAP was taken as the mean of a one-half second period of nearly constant IAP production. Three maximal pulsed pressures of approximately one-half second duration were also executed in the same standing position. Peak IAP was taken as the highest IAP value. The rate of pulsed pressure increase (dP/dt) was calculated as the slope between the onset and peak of the IAP signal.

Landing and jumping (initial and final tests only). Nine randomised drop-jumps were performed from three heights onto a force plate (Kistler Type 9281 B, Kistler Ltd., Switzerland). The subject stepped from a pre-determined height (20, 40 and 60 cm) and landed two-footed onto the force-plate (12). With as little time as possible spent in contact with the force-plate, the subject then performed an immediate maximal vertical jump. Vertical ground reaction force and IAP were recorded for each drop-jump.

Sudden trunk loading (initial and final tests only). Sudden loading was achieved with the subjects standing on a force plate (Kistler Type 9281 B; cf. above) and wearing a rigid plastic vest securely fastened to the torso. A 5-kg weight attached by a 25-cm long string to a metal rod which extended 12 cm ventrally from the vest was dropped unexpectedly to the subjects (10). Unexpected trials were performed dorsally in a similar way. Expected ventral perturbations were performed by the subjects releasing the weight themselves. Vertical ground reaction force and IAP were recorded simultaneously for the three trials of each condition. The latency of the IAP response to the perturbation was calculated from the time between the increases in vertical ground reaction force and IAP.

Statistics

Three trials were performed for each test with the mean value representing the test measurement. Differences in measurements were determined using a two-way analysis of variance (ANOVA) with one factor being the test and control groups, and the second being weeks of training (0, 5 and 10 weeks). *Post hoc* comparisons were performed to determine where any significant difference lay (Bonferroni test; Systat/Sygraph, Systat Inc, USA). Significance was set at the 0.05 level.

RESULTS

Training. No significant difference ($p > 0.05$) was seen between the training and control groups for the initial tests. The control group showed no significant change in any measured variable over the 10 weeks ($p > 0.05$). Therefore, results are hereafter reported only for the training group. Training subjects completed a total of 28 (SD 2) training sessions with 15 training sessions done prior to the mid-test after week 5. The mean training load increased 21% (SD 5.2) over the 10 weeks of training. The corresponding increase after 5 weeks was 14% (SD 3.7).

Strength and IAP. The training group showed a significant increase in isometric rotational force after the first 5 weeks of training with a mean increase for rotations in both directions being 19.6% (SD 2.6) ($p < 0.05$). A further increase was seen during the following 5 weeks which resulted in a total mean gain of 29.7% (SD 4.1) ($p < 0.05$). All subjects were asymmetric in trunk rotational strength at the time of the initial test (8.3% (SD 1.2) ($p < 0.05$) stronger when attempting to rotate toward the left). The increase in strength was also asymmetric over the training period with a 26.3% and 33.1% strength increase when attempting to rotate the trunk toward the left and right, respectively ($p < 0.05$).

Peak isometric flexor torque showed no change after 5 or 10 weeks of training, while peak isometric extensor torque increased 7.2% ($p < 0.05$) and 11.0% ($p < 0.05$), respectively (Table II).

The IAP measured during the isometric rotational test showed no significant change between the first,

Table II. *Isometric trunk flexor and extensor torques initially and after 5 and 10 weeks of dynamic rotational trunk muscle training*

Test condition	Initial test (Nm)	After 5 weeks (Nm)	After 10 weeks (Nm)
Isometric trunk flexion (MVC)	114.3 (SD 10.6)	117.0 (SD 12.8)	119.2 (SD 11.1)
Isometric trunk extension (MVC)	221.0 (SD 9.2)	238.4 (SD 11.6)*	248.2 (SD 12.9)*†

* Sign. diff. from initial test.
† Sign. diff. from 5-week test.

mid- and final tests (Table III). Intra-abdominal pressure measured initially at 50% of the maximal isometric force was 78% of that recorded during the maximum trial and showed no significant change after 5 and 10 weeks of training. No significant difference was seen after training for IAP during the maximal isometric trunk flexions and extensions (Table III).

Voluntary pressurisations. Peak IAP recorded during the maximal Valsalva manoeuvre showed an increase of 11.6% ($p<0.05$) after 10 weeks of training (Table IV). A 6.2% change after 5 weeks of training was not significant ($p>0.05$). For the series of shorter maximal pulsed pressures, peak IAP showed no significant change after the first 5 weeks (6.1%) ($p>0.05$) but increased 9.2% ($p<0.05$) after the full 10 weeks of training (Table IV). The rate of IAP development during the pulsed pressures did not change over the first 5 weeks of training (from 67.2 $kPa \cdot s^{-1}$ (SD 8.9) to 69.4 $kPa \cdot s^{-1}$ (SD 9.1) ($p>0.05$)). However, a significant increase in dP/dt occurred over the full training period (from 67.2 $kPa \cdot s^{-1}$ (SD 8.9) to 75.5 $kPa \cdot s^{-1}$ (SD 7.9) ($p<0.05$)). No significant increase was seen for either Valsalva or pulsed peak pressure variables between weeks 5 and 10.

Landing and jumping. A reproducible pattern of IAP and ground-reaction force was seen for each subject at a given height. An IAP increase always occurred prior to landing on the force-plate. The latency of this response (first landing) for the initial test for all heights was 705 ms (SD 94). No significant difference in latencies was apparent during the initial and final test with increased drop height. After 10 weeks training, the latency between IAP onset and impact on landing was reduced to 396 ms (SD 62) ($p<0.05$) resulting in an increase in the rate of IAP development.

The IAP signal displayed a three peak pattern over the course of the entire movement (Fig. 2). The first larger peak of pressure (initial mean of all subjects: 8.1 kPa (SD 1.6)) was coincident with the peak ground reaction force while the second smaller peak (6.5 kPa (SD 1.4) ($p<0.05$)) occurred while the subject was in the early flight phase of the jump. The third smallest increase of pressure (4.8 kPa (SD 1.4) ($p<0.05$)) began prior to final ground contact and peaked in time

Table III. *Peak IAP during initial maximal voluntary isometric trunk tests and after 5 and 10 weeks of dynamic rotational trunk muscle training*

Test condition	Initial test (kPa)	After 5 weeks (kPa)	After 10 weeks (kPa)
Trunk rotation (MVC)	11.8 (SD 1.4)	12.0 (SD 0.8)	12.4 (SD 1.6)
Trunk rotation (50% of MVC)	9.2 (SD 1.4)	8.7 (SD 1.1)	10.3 (SD 0.9)
Trunk flexions (MVC)	13.2 (SD 1.7)	14.4 (SD 1.2)	13.6 (SD 1.5)
Trunk extensions (MVC)	11.1 (SD 1.6)	12.3 (SD 1.4)	12.6 (SD 1.1)

Table IV. *Peak IAP during initial maximal voluntary pressurisations (Valsalva and pulsed pressure) and after 5 and 10 weeks of dynamic rotational trunk muscle training*

Test condition	Initial test (kPa)	After 5 weeks (kPa)	After 10 weeks (kPa)
Valsalva	11.9 (SD 0.83)	12.7 (SD 1.07)	13.3 (SD 0.98)*
Pulsed pressure	13.1 (SD 1.11)	13.7 (SD 1.17)	14.3 (SD 1.20)*

* Sign. diff. from initial test.

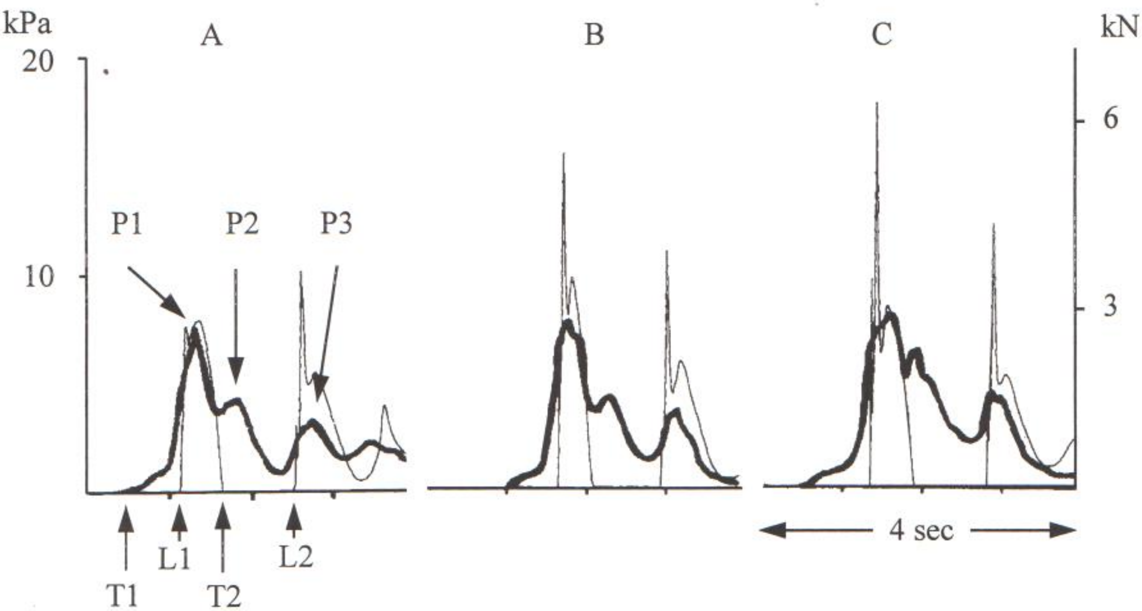

Fig. 2. IAP (thick line) and vertical ground reaction force (thin line) records for a representative subject performing the initial landing and jumping test from 20 cm (A), 40 cm (B) and 60 cm (C) drop heights. T1 indicates stepping off from the set height; L1 landing on the force-plate; T2 the jump take-off and L2 the final landing. P1-P3 represent the three IAP peaks.

with peak ground reaction force on landing. Even though peak ground reaction force increased with drop height (ranging from 2.5 to 6.5 kN, respectively ($p < 0.05$)) no significant differences for any of the IAP peaks were seen between drop heights. After training, the three IAP peaks were still evident during the task, and were not significantly different in magnitude from those recorded prior to training ($p > 0.05$).

Sudden loading. In the initial test, unexpected front loading resulted in a sudden increase in IAP, peaking at a value of 8.9 kPa (SD 1.5). Back loading produced IAP values greater than those during front loading (13.3 kPa (SD 1.4) ($p < 0.05$)). In self loading, IAP was developed prior to the perturbation, i.e., before the load reached the end of the string, and sharply increased to a peak once the perturbation was received (10.4 kPa (SD 1.2)). A period of 36 ms (SD 1.3) was recorded between the unexpected front loading perturbation and the first sign of IAP increase. This delay was longer for back loading (82 ms (SD 4.1); $p < 0.05$) while during self loading, IAP was developed some 192 ms (SD 17.1) ($p < 0.05$) prior to the perturbation.

After 10 weeks of training, no significant difference in the level of peak IAP was noted in the front and self-loading conditions (8.9 to 7.8 kPa and 10.4 to 9.6 kPa, respectively ($p > 0.05$)) nor for the back loading condition (13.3 to 13.1 kPa ($p > 0.05$)). Latencies between the perturbation and IAP onset were not different after training for the front or back loading conditions, while during the self loading condition the time between the pre-increase of IAP and perturbation was reduced to 131 ms (SD 9.6 ($p < 0.05$)).

DISCUSSION

The main findings of this study were that 10 weeks of rotational trunk muscle training, primarily involving the transverse and oblique abdominal musculature, resulted in an increase in isometric trunk rotational strength and an increase in the maximal level of IAP, which can be developed voluntarily. Levels of IAP generated during certain loading and functional tasks were largely unchanged, while improvement was seen after training in the rate of IAP development.

Previous strength training studies on abdominal muscles have concentrated on training the trunk flexors by way of sit-up and resisted trunk flexion training. Most of these studies have shown large strength increases in untrained subjects after 6–10 weeks of training (1, 13, 14, 15, 18, 19). The rotational strength increase in this study (29.7%) is comparable in magnitude to the increases in flexion strength for the earlier mentioned training studies. This increase in trunk rotational strength suggests that the abdominal oblique and transversus abdominis muscles have the potential to be stimulated toward increasing their force output and thus torque development. The degree of strength increase over the 10 week period that can be attributed to abdominal muscle hypertrophy is unknown. An attempt to answer this question was made by examining the abdominal muscle morphology with magnetic resonance imaging. Transverse sections at the umbilical level were imaged using a T1 weighted FLASH sequence. However, cross-sectional areas of the individual muscles of the ventro-lateral abdominal wall could not be resolved well enough to make any conclusion.

In the initial test, all subjects developed a greater amount of isometric rotational force in one direction. In all cases this occurred when maximally rotating back from the right. It is possible that this asymmetry is linked to hand dominance as all subjects within the study were right handed. Furthermore, all subjects were athletic and therefore likely to be producing forceful counter-clockwise trunk rotations more often than clockwise rotations during tasks like throwing and striking. A similar asymmetrical strength finding has been reported earlier in fencers (22), wrestlers, gymnasts, soccer and tennis players (3) who showed a greater lateral flexion strength on their non-dominant side as compared with non-athletes who were symmetric in lateral flexion strength. Increases in rotational trunk strength after the 10 week period were also disproportionate, with the greatest increase occurring when twisting back from the left. Even though the clockwise rotation, which was initially the weakest, showed the greatest strength increase, the strength improvement was not enough, however, to overcome the original differential and result in symmetrical rotational strength.

The training device was specific in its design to increase trunk rotational strength. This was highlighted by the fact that no significant increase in trunk flexor torque occurred over the 10 week period, despite the fact that obliquus externus and internus have fibres running in a direction that allows them to contribute toward trunk flexion. The increase in trunk extensor torque over the training period indicates, however, that the erector spinae muscle was also trained during the dynamic trunk rotations. Evidently, its involvement in both stabilising and rotating the lumbar spine during the trunk rotations was sufficient to afford a training stimulus.

The level of IAP recorded during maximal isometric trunk rotations (12 kPa) was at a level similar to that recorded for maximal isometric trunk flexions and extensions here and in earlier studies (8, 9). Trunk rotations performed at 50% of the maximum force level produced levels of IAP that were 22% less than those recorded in the maximum condition, indicating that the relationship between loading and IAP during trunk rotations is not one to one. Despite the fact that the rotational force was approximately 30% greater after training, IAP measured during the maximal isometric rotations was unchanged, showing that the degree of loading is not the exclusive factor which determines the level of IAP to be generated. This was also highlighted by the lack of any significant difference between the initial IAP level for isometric rotations performed at 50% of maximum and the final IAP level at 50% of the new isometric maximum. What mechanism(s) is involved in setting and controlling the required level of IAP during this type of task is at present unknown. Although not measured here, the level of IAP that would occur for a contraction at the initial 50% force level after training is likely to be less than the level achieved in the initial test. It therefore seems likely that the level of IAP generated during a task such as this is more coupled to the relative load and/or the sense of effort, than to the absolute load required by the task. A similar relationship has also been seen for IAP and force during isokinetic lifting and lowering (unpublished) and has been partially attributed to the level of activation of the back extensors and not the load itself.

The level of IAP can be increased substantially by voluntarily closing the glottis and forcefully contracting the ventro-lateral abdominal wall and diaphragm. This voluntary manoeuvre (Valsalva) develops high levels of IAP which can be held for only a few seconds before the vascular system becomes compromised. This manoeuvre is commonly used among combat pilots to prevent blackout during high G-force aerial manoeuvres. The increase in IAP that could be produced both by the Valsalva manoeuvre and pulsed pressures and the increase in rate of IAP development after rotational trunk training shows, unlike other studies (5, 13, 14), that training of the abdominal muscles can influence the level and rate of pressure that can be generated intra-abdominally. The design of the rotational training performed in this study was based upon our earlier intra-muscular electromyographic findings of the oblique and, in particular, transverse musculature being activated during trunk rotations and IAP production (8, 9). The training design in this study separates it from an earlier G-tolerance training study (5) which showed no significant improvement in either IAP development or G-tolerance after 11 weeks of static abdominal training. It is therefore believed that improvement of G-tolerance can be produced by specific dynamic training of the trunk rotator muscles.

The occurrence of an increased IAP when landing from a height has been reported earlier (12). It was suggested that this pressure increase would reduce spinal comprehensive force and increase the overall stability of the trunk. The development of an IAP increase prior to contacting the ground, both in the initial and final landing, indicates the existence of a neural strategy designed to prepare the trunk for a known oncoming disturbance. The three distinctive peaks of pressure timed to the initial landing, subsequent flight and final landing support the idea of a functional role played by the pressure increase to reduce forces within the spine on landings and/or stabilise the rapid flexion and extension of the trunk during both the landing and maximal jump, respectively. The only parameter that changed with training was the reduction in time from when IAP first began to increase and the initial ground contact, indicating, as for the maximal pulsed pressures, an improvement in the rate of IAP development. It is these changes that attest to an improved ability for the abdominal muscles (and possibly the diaphragm) to increase IAP in a more rapid way. It is unknown, however, if this enhancement is a result of improved coordination between all of the pressure developing muscles or a direct result of any physical changes that may have occurred in these muscles via training.

It has been shown earlier that IAP increases in a reflex manner to sudden unexpected perturbations delivered to the trunk while standing (10). A feed-forward increase of IAP prior to expected trunk perturbations, similar to the early IAP response seen in the previously mentioned drop jumps, was also observed. The amplitude and latency of this action have possible implications for both balance control and injury prevention of the lumbar and cervical spine. The sudden expected and unexpected trunk loadings used here produced large increases in IAP that were of the same magnitude and timing as those seen in the earlier study (10). The decrease in latency between the initial increase in IAP and the onset of perturbation in the self loading condition was the only significant change over the 10 weeks of training. This reduced time supports the previously mentioned idea that an improved coordination of the pressure developing muscles has taken place with training. As no change occurred in the level of IAP that was generated, it may be concluded that the magnitude of the IAP response required to stabilise the trunk was within the initial capable limits of these individuals.

In conclusion, 10 weeks of training of the trunk rotator muscles influenced the magnitude and rate of the IAP increase. The levels of IAP developed during the trunk loading tasks were, however, largely unchanged. It is suggested that it is not necessarily the absolute trunk load which governs the level of IAP but more the relative effort of the task. The improvement in the rate of IAP development during the jumping and the sudden trunk loading tests indicates this factor as an important mechanism in trunk stabilisation and control.

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