

Muscular Performance Assessment of Trunk Extensors: A Critical Appraisal of the Literature

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1. Introduction

Despite growing research efforts, non-specific low back pain (LBP) remains a major public health burden throughout the industrialized world. Epidemiological data indicate a point prevalence ranging from 19% (Hillman et al., 1996) to 27% (Picavet & Schouten, 2003) and a lifetime prevalence of about 60% (Hillman et al., 1996). Costs to society stem mainly from chronic forms, which account for only 5–10% of cases (Nachemson et al., 2000).

Some literature suggests that muscle dysfunction or increased fatigability might jeopardize the function of the spine and be a risk factor in the development, persistence or recurrence of LBP (Biering-Sorensen, 1984; Parnianpour et al., 1988; Alaranta et al., 1995; Hides et al., 1996). Besides, several studies suggest that patients with chronic low back pain (CLBP) may benefit from an active multidisciplinary approach involving an individually tailored reconditioning program (Bendix et al., 1998; Smeets et al., 2008; Demoulin et al., 2010); some authors even reported benefits of programs based mainly on trunk muscles training (Manniche et al., 1988; Mooney et al., 1995; Nelson et al., 1995; Carpenter & Nelson, 1999; Mannion et al., 1999b). As a result, tests of trunk muscle performance are essential to get insight in the muscle strength/endurance. Furthermore, accurate evaluation of patients' deficiencies is essential for the planning of a successful rehabilitation program, for documenting program efficacy and for providing the patients with information on their physical potential and ability to make progress, thereby leading to favourable behavioural changes. Therefore, several reviews have been published targeting performance of trunk muscles (Beimborn & Morrissey, 1988; Newton & Waddell, 1993; Moreau et al., 2001; Malliou et al., 2006). Currently, assessments are performed by means of various methods and no consensus has been reached regarding the optimal test to be used. Most of the time, assessment of trunk extensors has been performed by means of maximum effort tests;

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however, alternatives to maximum effort tests have also been developed. Therefore the aim of the current review is to present a critical appraisal of the literature on this topic.

2. Assessment of trunk extensors by means of maximum effort tests

2.1 Non-dynamometric tests

Trunk extensor performance has been measured with clinical tests for more than 50 years (Hansen, 1964). These tests, which usually assess endurance of trunk extensors, have the main advantages that they don't require specific equipment, are inexpensive, quick and easy to perform. However, they are not adapted to assess muscle strength and they do not provide a stabilization system to limit hip extensors activation (making them unable to assess spinal muscles specifically). These tests have most often been used in healthy subjects and in patients with CLBP, but they have also been used in other populations (e.g. patients after back surgery (Hakkinen et al., 2003), in schoolchildren (Salminen et al., 1992), etc.).

2.1.1 Static tests

The **Sorensen test** is by far the most widely used and studied test for assessing trunk extensor muscles (Demoulin et al., 2006b). In this test, the subject lies on an examining table in the prone position with the pelvis aligned with the edge of the table. Calves, thighs, and buttocks are secured and upon command, the subject is asked to maintain the horizontal position as long as possible with the arms folded across the chest (Fig 1a). This test was first described by Hansen in 1964 (Hansen, 1964), but it became known as the "Sorensen test" following a study by Biering-Sorensen in 1984, according to which good isometric endurance might prevent first-time LBP occurrence (Biering-Sorensen, 1984). Although some authors have reported similar findings (Alaranta et al., 1995; Adams et al., 1999; Sjolie & Ljunggren, 2001), such association was not confirmed in other studies (Salminen et al., 1995; Gibbons et al., 1997b; Hamberg-van Reenen et al., 2006).



Fig. 1a. Original Sorensen test

Fig. 1b. Sorensen test with a Roman chair

Since 1984, the Sorensen test has been used in several studies, either in its original or in adapted versions: the differences concerned the arm position, number of straps, criteria for stopping the test, etc. (Demoulin et al., 2006b); the test has also been performed on a roman chair (Fig 1b) in a few studies (Hultman et al., 1993; Mayer et al., 1995; Keller et al., 2001), sometimes with 45 degrees of hip flexion (Champagne et al., 2008). These numerous

methodological variations can affect muscle activity considerably (Mayer et al., 1999; Champagne et al., 2008) and result in considerable discrepancies in study findings. However, concordance was found between some studies regarding the mean holding time in healthy subjects: whereas Latimer et al. measured a holding time of 133s in mixed males and females (Latimer et al., 1999), Mannion et al. reported a holding time reaching 142s and 116s in females and males, respectively (Mannion & Dolan, 1994). Such a gender-related difference was reported in most other studies (Biering-Sorensen, 1984; Mannion et al., 1997a; Kankaanpaa et al., 1998a; McGill et al., 1999; Muller et al., 2010). Differences between genders regarding the weight of the upper body, the degree of lumbar lordosis, the muscles composition (Demoulin et al., 2006b) and the neuromuscular activation patterns (Lariviere et al., 2006) are all hypotheses mentioned.

The Sorensen test has sometimes been considered as a specific tool for evaluating the back muscles (Alaranta et al., 1995). Although spinal muscles are really solicited, most notably the multifidus muscle (Ng et al., 1997; Coorevits et al., 2008; Muller et al., 2010), the test solicits also the other muscles involved in extension of the trunk i.e. the hip extensor muscles (Kankaanpaa et al., 1998a; Plamondon et al., 2002; Plamondon et al., 2004; Champagne et al., 2008; Coorevits et al., 2008; Muller et al., 2010). However muscle fatigue of the hip extensor muscles (reflected by electromyographic parameters) is less correlated to the test holding time than back muscle fatigue (Coorevits et al., 2008).

Although some authors call it a "strength test" (Salminen et al., 1992; Tekin et al., 2009), it rather assesses muscle static endurance (Crowther et al., 2007). Indeed, the elicited contractions were found to be no greater than 40-52% of the maximal voluntary contraction (MVC) (Mannion & Dolan, 1994; Ng et al., 1997; Plamondon et al., 1999; Muller et al., 2010) and the electromyographic (EMG) activity of the spinal erector muscles rarely exceeded 40% of its maximal value (Plamondon et al., 1999; Plamondon et al., 2002).

Although the reproducibility of the Sorensen test has been evaluated in several studies, most of these suffered from methodological weakness (Essendrop et al., 2002; Demoulin et al., 2006b). In general, investigations reported a moderate or high[†] intra-session, inter-session and inter-tester reproducibility (Simmonds et al., 1998; Latimer et al., 1999; Demoulin et al., 2008b; Gruther et al., 2009), except in case a Roman chair was used (Mayer et al., 1995; Keller et al., 2001). Although the reproducibility is satisfactory in patients with LBP (Simmonds et al., 1998; Latimer et al., 1999) it might be relevant to repeat the test twice (with a 15-minute rest in between) to avoid a learning effect which has been found in some patients (Demoulin et al., 2008b).

Most studies have reported a good discriminative validity of the Sorensen test reflected by a holding-time being significantly lower in patients with LBP compared to healthy subjects (Biering-Sorensen, 1984; Hultman et al., 1993; Simmonds et al., 1998; Latimer et al., 1999; Ljungquist et al., 1999; Arab et al., 2007; Gruther et al., 2009). The safety of the test has also been investigated. A small number of subjects reported back pain during the test (Demoulin et al., 2008b; Demoulin et al., 2009), sometimes resulting in the interruption of the test (Biering-Sorensen, 1984; Latikka et al., 1995; Latimer et al., 1999); however, no persistent adverse effects have been reported following the test (Simmonds et al., 1998; Demoulin et

[†] based on the classification of Wind et al. (*J Occup Rehabil*, 2005, 15(2):253-272) which will also be used in the rest of the chapter.

al., 2008b) and it could even be applied in elderly people (Champagne et al., 2009). In view of the stress induced on the cardiovascular system, the Sorensen test might better be avoided in patients suffering from cardiovascular disease because of a pressure overload of the cardiovascular system (Sunı et al., 1998; Demoulin et al., 2009).

The **Ito test**, sometimes called “prone isometric chest raise test”, has been described in a couple of studies (Shirado et al., 1995b; Ito et al., 1996; Arab et al., 2007; Durmus et al., 2009; Muller et al., 2010); it consists of lifting the upper body while lying prone with a pad under the abdomen, the arms along the sides, the neck flexed as much as possible and the gluteus maximus muscles contracted for stabilizing the pelvis (Fig. 2a) (Shirado et al., 1995b); this position has to be held as long as possible (Ito et al., 1996). Its discriminative power and high reproducibility were reported in the original study (Ito et al., 1996); furthermore, fatigue of the iliocostalis and the multifidi has clearly been linked to the holding time (Muller et al., 2010). Although this test is attractive because it is easy to perform and because it seems to induce less spine loading and limit the risk of lumbar hyperlordosis as compared to the Sorensen test (Ito et al., 1996), no study really confirmed this assumption. Furthermore, a study suggested that this test was less comfortable and more difficult to standardize (with regard to the extent of the upper body lift) than the Sorensen test (Demoulin et al., 2008b). These differences might explain the controversial correlations found when comparing holding times of both tests (Demoulin et al., 2008b; Muller et al., 2010).

The **prone double straight-leg raise test** has been described for evaluating the isometric endurance of the lower spinal extensor muscles (McIntosh et al., 1998; Moreau et al., 2001). In this test, the subject lies prone with hips extended and the hands underneath the forehead (Fig. 2b). The subject is asked to raise both legs until knee clearance as long as possible. According to Arab et al., this test is as reproducible as the other static endurance tests and has good sensitivity, specificity and predictive values in LBP (Arab et al., 2007). However, information about its validity, safety and responsiveness is lacking.

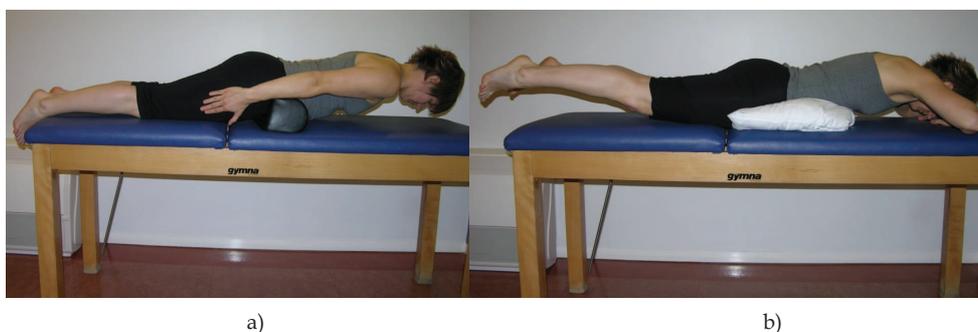


Fig. 2. a) Ito test, b) Prone double straight-leg raise test

2.1.2 Dynamic tests (“arch-up tests”)

The “arch-up tests”, sometimes considered as dynamic variants of the Sorensen test, are usually used to assess dynamic endurance of trunk extensors. These tests, performed with the subject prone with the torso cantilevered over the edge of a table, consist in flexing the trunk to a specific position (e.g. 30° trunk flexion), then returning to the initial position as

many times as possible at a determined rate of arch-ups per minute (Fig. 3) (Alaranta et al., 1994; Gronblad et al., 1997; Moreland et al., 1997; Udermann et al., 2003). Whereas the static tests have been widely studied, the dynamic tests have received less attention and have been performed in various ways regarding the support (examination table, roman chair, etc.), the range of motion, the rate per minute, etc. As the original Sorensen test, the dynamic tests are not specifically testing the back muscles (Konrad et al., 2001). Although moderate reliability is suggested (Alaranta et al., 1994; Moreland et al., 1997), little is known about the other clinimetric properties of such tests. Furthermore, a recent study, which compared the static Sorensen test with its dynamic variant, revealed that the latter was less comfortable and more difficult to standardize (Demoulin et al., 2008b). In a few studies, the subjects were asked to perform as many repetitions as possible in 30 seconds (Viljanen et al., 1991; Kujala et al., 1996).



Fig. 3. Arch-up test

2.2 Dynamometric tests

Today, various dynamometric testing machines have been developed to assess trunk muscle performance: these tests allow more complete, precise and specific assessments than the non-dynamometric tests. These measurement systems, also designed to train muscles, differ in terms of contraction mode (static, isotonic, isokinetic), subject position (standing, sitting, lying prone) etc., and generally enable the assessment of several muscular qualities.

2.2.1 Muscle strength tests

MVC tests of trunk extensor muscles have been used in several studies to assess maximal strength in healthy subjects and patients with LBP but also in other populations (e.g. patients following back surgery (Hakkinen et al., 2003), elderly subjects (Rantanen et al., 1997), etc.). Patients with CLBP had reduced values compared to healthy controls in most studies (Reid et al., 1991; Hultman et al., 1993; Kankaanpaa et al., 1998b; Handa et al., 2000; Bayramoglu et al., 2001; Kramer et al., 2005; Gruther et al., 2009), but not all studies (Shirado et al., 1992; Cassisi et al., 1993; Takemasa et al., 1995; da Silva et al., 2005). Several methods (see below) have been used for testing maximal strength.

2.2.1.1 Static strength test

Usually, after a muscular warming-up and sometimes a familiarization period, the subject is instructed to build up the force with increasing intensity. In most studies, about three MVC are measured at short periods intervals; sometimes additional trials are permitted and the best result of the contractions is selected (Demoulin et al., 2006a; Schenk et al., 2006).

Trunk extensors strength can be assessed by means of a **hand-held dynamometer** that is held by the investigator in the interscapular area; the subject, lying prone, has to perform a maximal static effort against it (Fig. 4a). This test which has been confidentially described (Moreland et al., 1997; Swezey et al., 2000; Durmus et al., 2009) appears to be difficult to perform in a standardized manner (Moreland et al., 1997; Swezey et al., 2000) and has a low reproducibility (Moreland et al., 1997).

MVC of trunk extensors has also been assessed by means of a **strain gauge** (Fig. 4b) attached to a wall and connected to a strap around the shoulders; a pelvic fixation is provided so that the rotation axis is set at the hip joint level. The subject, in standing position, has to perform an isometric backward extension ("pulling test") (Biering-Sorensen, 1984; Nicolaisen & Jorgensen, 1985; Kumar et al., 1995; Kujala et al., 1996). In some studies, a more sophisticated apparatus (e.g. with a frame) has been developed (da Silva et al., 2005). Tests in sitting (Kumar et al., 1995) or in prone positions (Plamondon et al., 2004; da Silva et al., 2005) have also been described. Reliability of the pulling tests seems high to moderate (Jorgensen, 1997; Lariviere et al., 2001); however, little is known about the other clinimetric qualities.

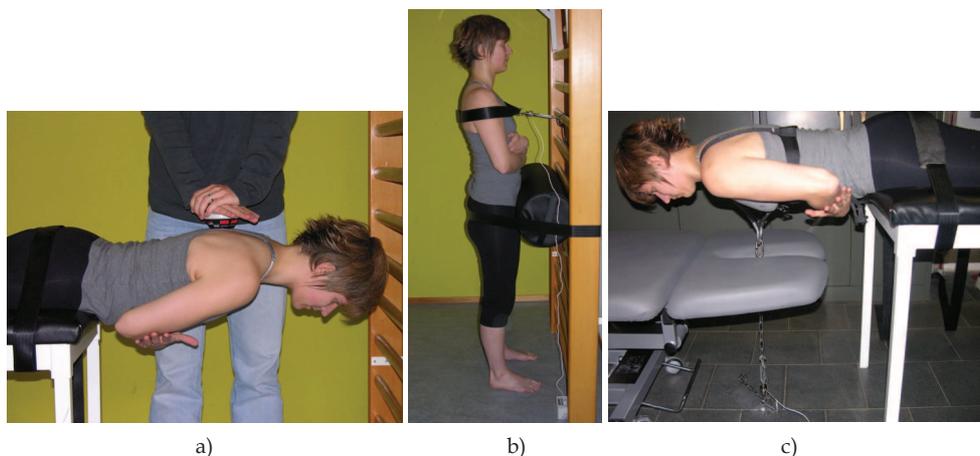


Fig. 4. a) Hand-held dynamometer, b) "Pulling test" in standing position, c) "Pulling test" in prone position

Specialized and commercialized equipments have also been developed to assess and train trunk muscles. The subject is seated in the equipment and a control of the pelvis is provided by means of a stabilization system designed to limit the activation of hip extensors (Graves et al., 1994; San Juan et al., 2005; Smith et al., 2008); however relevance of such stabilization systems which differ from one device to another remains controversial (Udermann et al., 1999; Walsworth, 2004).

Most studies concerned the MedX™ (MedX Corp. Ocala, FL, USA) which is a dynamometer developed to assess and train spinal muscles (Graves et al., 1990) (Fig. 5). MedX™ assessment consists of measuring the extensor isometric MVC at 7 angles of trunk flexion within the patient's range of motion (i.e. 0-12-24-36-48-60-72°) (Graves et al., 1990). This device is unique in the fact that it uses a gravity correction system (Pollock et al., 1991; Graves et al., 1994). Literature suggests a moderate to high reproducibility of peak torque values in healthy individuals (Graves et al., 1990) and patients with CLBP (Robinson et al., 1992).



Fig. 5. MedX™, David® and Tergumed® dynamometers, respectively

Other companies (David®, Tergumed®, Schnell®, DBC®) propose a complete set of four individual units for training (Taimela & Harkapaa, 1996; Daniels & Denner, 1999; Mannion et al., 1999b; Gienza et al., 2006) and assessing the trunk extensor, flexor, rotator and lateral-flexor muscles, respectively (Demoulin et al., 2006a; Roussel et al., 2008). The extension device (Fig. 5) differs between the various systems of the companies regarding the hip stabilization system, position of the thighs, legs and feet, etc. Although these protocol differences might concur meaningful inter-system comparison, significant correlations were observed between the MVCs measured by the David®, Tergumed® and Schnell® systems as well when considering the absolute values ($r \geq 0.8$) as when considering the relative values expressed in percentage of specific normative data ($r \geq 0.69$) (Demoulin et al., 2008a). Although spinal muscles seem to be well activated ($\geq 80\%$ maximal EMG activity) during an isometric extension MVC on such dynamometers (Denner, 1997; Vanderthommen et al., 2007), a significant activation of hip extensor muscles has also been observed (about 50% of maximal EMG activity) (Vanderthommen et al., 2007). Several authors reported a high inter-session (Elfving et al., 1999; Demoulin et al., 2006a) and inter-tester (Demoulin et al., 2006a) reproducibility of MVC measurements in healthy subjects and in patients with CLBP (Elfving et al., 2003; Roussel et al., 2008); however, the inter-site reproducibility (in healthy subjects) revealed small but significant differences in measurements between identical devices (Demoulin et al., 2006a). The cardiovascular stress of such maximal isometric effort seems to be limited in healthy middle-aged individuals (maximal systolic and diastolic blood pressure monitored at the end of the MVC test: 165 and 105 mmHg, respectively) (Demoulin et al., 2009); however these results need to be confirmed with instantaneous blood pressure measurement.

A positive relationship between lifting and LBP has been reported (Cole & Grimshaw, 2003); as a result some **functional assessments (lifting test)** have been developed to measure the strength of the functional chain (upper limbs-trunk-lower limbs) during static lifting tasks (Newton et al., 1993; Mannion et al., 1997a; da Silva et al., 2005; Ropponen, 2006). While standing and bending forward, the subject is asked to pull upward a handlebar which is fixed by a chain to a floor-mounted load cell. Methods of testing described in the literature differ regarding materials, knee flexion, the bar height, etc. Though it is a lifting task, the real functional aspect of such test remains questionable because it involves no movement; the safety of such lifting maximal isometric task remains also controversial (Hansson et al., 1984). Limited evidence is available about the clinimetric qualities of such tests.

2.2.1.2 Isokinetic test

Isokinetic dynamometry has been one of the most widely used approaches to train and measure strength of trunk muscles (Newton et al., 1993) for more than 30 years (Hasue et al., 1980). Such dynamometers can measure **trunk flexion and extension strength** (allowing to calculate agonist/antagonist ratios (Newton et al., 1993))(Fig. 6a), at various angular speeds and contraction modes (concentric most often but also eccentric (Shirado et al., 1992) and isometric (Bayramoglu et al., 2001; McGregor et al., 2004; Gruther et al., 2009)). Another advantage of isokinetic dynamometry is that it provides a variable resistance accommodating to a painful arc during the movement. Test-retest reliability of isokinetic measurements appears high in healthy subjects in most studies (Delitto et al., 1991; Newton et al., 1993; Keller et al., 2001; Karatas et al., 2002). In patients with LBP, an increase in performance between test and retest, interpreted as "learning effect", has often been reported (Grabiner et al., 1990; Newton et al., 1993; Keller et al., 2001; Gruther et al., 2009). Inter-site reliability, tested in healthy volunteers, also seems to be high (Byl & Sadowski, 1993).

However, use of isokinetic dynamometry to perform trunk muscle assessment suffers from several limitations: although some authors tried to propose a standard method of testing (Dvir & Keating, 2001), no consensus has been established yet regarding the optimal parameters for testing i.e. movement speed (which can affect testing accuracy (Keller et al., 2001)), range of motion, number of repetitions (Genty & Schmidt, 2001), etc. Differences between the existing isokinetic trunk testing machines in terms of subject position (sitting vs standing)(Morini et al., 2008), ways to reduce the artefacts, stabilization system, gravity correction system (Hupli et al., 1997; Findley et al., 2000) limit meaningful inter-system comparison (Hupli et al., 1997). Besides, the stabilization systems might be inefficient to avoid involvement of hip muscles, especially in the standing position (Morini et al., 2008). Finally, according to some authors (Ayers & Pollock, 1999), the validity of the isokinetic tests of trunk extensors remain controversial due to the impact forces at the end of the movements which can induce artefacts (overshoot). Furthermore, these tests could induce vagal disturbances (Genty & Schmidt, 2001) and pain during testing (Shirado et al., 1995a; Genty & Schmidt, 2001).

Isokinetic dynamometer has also been used to measure the **strength of the functional chain (lifttask)** (Newton et al., 1993; Latikka et al., 1995; Gibbons et al., 1997b; Ropponen, 2006). As for the static lifting tests, various methods of testing have been described in the literature; besides, though it is a lifting task, the real functional aspect of such test remains

questionable because it involves a movement in a constant speed. Limited evidence is available about the clinimetric qualities of such tests except for reliability which is high in LBP patients and healthy subjects (Newton et al., 1993; Latikka et al., 1995). The high correlations found between the isokinetic flexion-extension and lifting tests suggest that performing both tests is not necessary in clinical practice (Newton et al., 1993).

2.2.1.3 Isoinertial measurements

The Isostation B-200® (Fig. 6b) has been used in a huge number of studies to assess trunk muscle performance but is less used nowadays. In addition to mobility and isometric MVC measurements, this triaxial lumbar dynamometer allows for isoinertial tests (i.e. use of a constant load throughout the range of motion) (Parnianpour et al., 1989b; Gomez et al., 1991; Balague et al., 2010). For the isoinertial flexion-repetition test, the resistance (free weights) is set at a determined percentage of the MVC of flexion (e.g. 25% or 50% (Hutten & Hermens, 1997)) for the sagittal axis and the subject is asked to bend and then return backward as fast as possible (maximum effort) about five times while functional indices (maximal or average velocity, power index and work index) can be simultaneously assessed (Gomez et al., 1991; Rytokoski et al., 1994). This assessment appears to be safe (Newton & Waddell, 1993) and reliable (Rytokoski et al., 1994) as well in healthy persons (Parnianpour et al., 1989a) as in patients with CLBP (Szpalski et al., 1992; Hutten & Hermens, 1997) except for mobility assessments. Unfortunately, axis of rotation of the device is behind the estimated axis for lumbar spine for flexion and extension (Dillard et al., 1991). Furthermore, the device might be inefficient to fully stabilize the pelvis and its relevance to improve functional physical capacity remains controversial (Sachs et al., 1994).

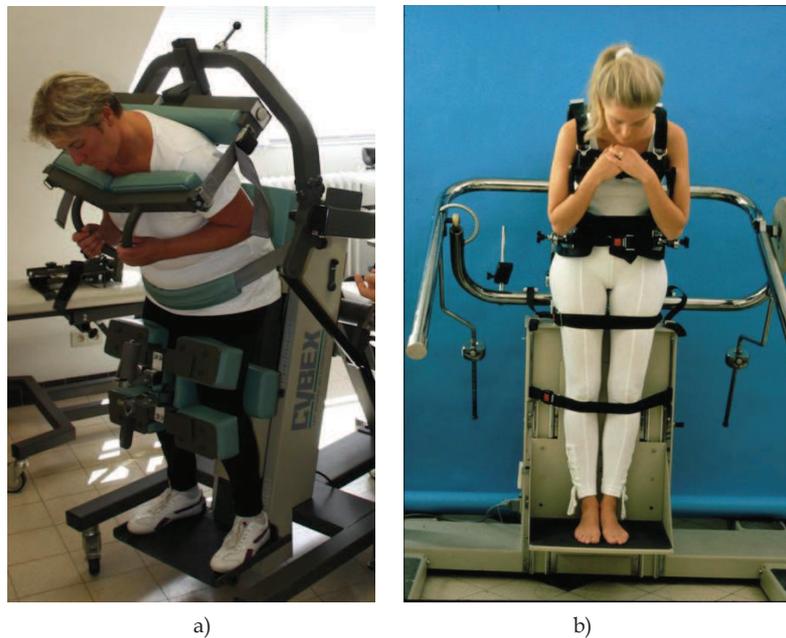


Fig. 6. a) Isokinetic dynamometer, b) Isostation B-200®

2.2.2 Endurance tests

2.2.2.1 Static endurance

Muscle static endurance can be assessed with several dynamometers by measuring the time during which a subject is able to maintain a specific torque level corresponding at a preset relative percentage (often 40-60%) of the MVC previously determined (Jorgensen, 1997; Kankaanpaa et al., 1998b; Udermann et al., 2003; Demoulin et al., 2009). A visual feedback system, displaying the torque in real time, is generally positioned in front of the subject in order to keep a constant torque. This test performed in standing position, used for more than 25 years (Nicolaisen & Jorgensen, 1985), is sometimes considered to be more appropriate than the Sorensen test because it is less sensitive to heterogeneous physiques (Jorgensen, 1997; Kankaanpaa et al., 1998a; da Silva et al., 2005). Demoulin et al. compared a seated endurance test performed on a specific dynamometer (David®) (Fig. 7a) to the Sorensen test in healthy subjects; they reported limited pain in the back during performance of both tests and similar subjective level of exertion and cardiovascular stress (Demoulin et al., 2009). As for the MVC test performed on this device, this seated endurance test induces hip extensors activation in spite of the hip stabilization system (Kankaanpaa et al., 1998b); unfortunately, this endurance test has a low test-retest reliability as well in healthy subjects as in patients with CLBP (Demoulin, 2008). Static endurance of trunk extensors have also been measured while the subject performs a lifting test (Mannion et al., 1997a; da Silva et al., 2005); however, such tests produce less fatigue in the back muscles than the Sorensen or the pulling tests (da Silva et al., 2005).

2.2.2.2 Dynamic endurance

Muscle dynamic endurance can be assessed with dynamometers by measuring the maximal number of repetitions performed with a specific load, with a preset speed and range of motion. The literature reports only few studies using such tests: on the David® device (Fig. 7b), the load used corresponded to $[0.4 \times \text{height (meter)}] \times [0.6 \times \text{Weight (kg)}] \times 0.82$ (Kankaanpaa et al., 1997). This test seems to be less reproducible and well tolerated than the MVC strength and static endurance tests (Demoulin, 2008). Similar tests have been described with the Isostation B-200® (Morlock et al., 1997) and the MedX™ (Udermann et al., 2003).

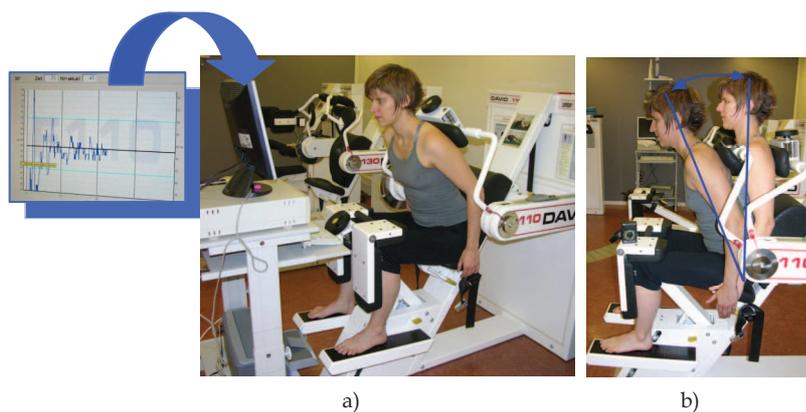


Fig. 7. a) Static endurance test, b) Dynamic endurance test

2.2.3 Muscle fatigue tests

Muscle fatigue can be defined as “an exercise-induced reduction in the ability of muscle to produce force or power whether or not the task can be sustained” (Enoka & Duchateau, 2008). Fatigue can be calculated by comparing the maximal strength (MVCs) prior and after an exhaustion task; in the study of Al-Obaidi et al., the task consisted in performing as many extension movements as possible against a predefined individual resistance (corresponding at 50% of the pre-MVC) (Al-Obaidi et al., 2003). Plamondon et al. submitted healthy students to an intermittent prone back extension exercise (100 dynamic repetitions) and reported fatigue of trunk extensors according to the decrease of MVC values (14-20%) measured with a strain gauge in a prone position (Plamondon et al., 2004). Corin et al. compared several ways to test muscle fatigue (Corin et al., 2005) but according to our knowledge, no study has really investigated the clinimetric properties of such assessments.

The isokinetic dynamometers enable to assess fatigue resistance of trunk extensors by requiring more than 15 repetitions at maximal intensity; the torque decrease (fatigue index) throughout the test is generally considered as a good indicator of fatigue resistance (Cale-Benzoor et al., 1992; Genty & Schmidt, 2001; McGregor et al., 2004). The high cardiovascular stress induced by such tests, which can be an important factor-limiting performance (Rantanen et al., 1995), might explain why they have been poorly investigated; furthermore, dizziness has been reported after such exercise (Peel & Alland, 1990) and a huge increase in heart rate (HR), which could reach 90% of maximal theoretical HR at the end of 20 repetitions, was reported (Rantanen et al., 1995). Therefore, caution is needed when testing patients with suspected heart problems (Rantanen et al., 1995).

Nowadays, for fatigue assessment, the surface electromyography (S-EMG) technique is often used and coupled to the endurance tests previously described, which are most of the time limited in time; thus S-EMG is used as an alternative to maximum effort tests to assess trunk muscle performance (see below).

2.3 Interpretation of results

Maximum effort tests have generally pointed out decreased trunk muscle performance in patients with CLBP. Most authors having observed such changes suggested that they could result from physical deconditioning and the associated alterations in the size (decrease in cross-sectional surface area of spinal muscles), density (fatty infiltration) and structure (fibers size reduction) of the trunk muscles (Hultman et al., 1993; Gibbons et al., 1997b; Raty et al., 1999; Danneels et al., 2000; Barker et al., 2004; Demoulin et al., 2007). However, several more recent papers consider that there is minimal research evidence that patients with CLBP really suffer from disuse, physical deconditioning (Smeets & Wittink, 2007; Verbunt et al., 2010) and morphologic alterations (Crossman et al., 2004; Smeets & Wittink, 2007; Verbunt et al., 2010).

The decrease in performance found in patients could partly result from of a lack of validity of such assessments which require maximal collaboration of subjects to produce a maximal effort in terms of intensity or duration (Newton & Waddell, 1993). Therefore, results can be influenced by several individual confounding factors such as motivation, pain tolerance, competitiveness (Mannion & Dolan, 1994); furthermore pain on exertion, anticipation or fear of pain and reflex inhibition of motor activation can be additional factors resulting in

inability or unwillingness to produce a truly maximal effort in patients with LBP (Menard et al., 1994; Vlaeyen et al., 1995; Crombez et al., 1996; Keller et al., 1999; Rashedi et al., 2003; Rainville et al., 2004; Al-Obaidi et al., 2005; Ropponen et al., 2005; Verbunt et al., 2005; Thomas et al., 2008; Huijnen et al., 2010). These individual factors might explain the absence or low correlations found in some studies between morphologic variables and performance (Parkkola et al., 1993; Gibbons et al., 1997a). They might also explain the significant learning effect observed in some patients, reflected by performance higher at the second trial than at the first one (Grabiner et al., 1990; Newton & Waddell, 1993; Lariviere et al., 2003b; Gruther et al., 2009). Such learning effect might explain partly the increase in trunk extensor performance sometimes observed after only a few training sessions (Mannion et al., 2001; Demoulin et al., 2010). Therefore, such increase in performance should always be interpreted with caution.

Therefore, although several studies reported no or low correlations between pain or disability and trunk extensor performance (Newton et al., 1993; Gronblad et al., 1997; Bayramoglu et al., 2001; da Silva et al., 2005), these maximum effort tests could also be considered as psychophysical test, reflecting in some cases more the fears and pain tolerance than the muscle function. Consequently, the relevance of using such tests in very painful patients is doubtful. Besides, a period of familiarization with the test appears absolutely necessary in order to eliminate the learning effect and the risk to underestimate real performance.

The technique of twitch interpolation seems a research method able to identify the role of non-physiological factors during strength testing (Verbunt et al., 2003). It is based on the registration of a twitch contraction elicited by a supramaximal electrical stimulus delivered to the muscle or nerve during a MVC. The force increment in response to this stimulus reflects the muscle force reserve or the difference between the maximum force that can be generated by the muscle and the maximum voluntary contraction force, in which nonphysiological factors play a role (Verbunt et al., 2003). This technique was used to compare healthy subjects with patients with LBP regarding knee extensor inhibition in a few studies (Suter & Lindsay, 2001; Verbunt et al., 2005); a lower central activation ratio was reported in patients experiencing increased psychological distress and with higher pain intensity (Verbunt et al., 2005).

3. Alternative to maximum effort tests to assess trunk muscle performance

A few studies examined whether trunk extensor strength could be predicted by anthropometric variables (Mannion et al., 1999a; Wang et al., 2005); indeed, such a prediction is of particular interest in patients who cannot perform maximal tests in order to determine appropriate loads for rehabilitation training (Mannion et al., 1999a). If these variables seem to influence muscle performance, their ability to predict accurately muscle capacity remains limited (Lariviere et al., 2003b).

Taimela et al. developed a submaximal dynamic back extension endurance test utilising subjective perception of low back fatigue (Taimela et al., 1998). They reported that the perceived fatigue (assessed by means of a Borg scale every 15 seconds) increased faster in patients with LBP disorders than in healthy subjects and suggested that this test might be a low-risk, low-cost evaluation method for assessing LBP patient when combined with other

clinical data (Taimela et al., 1998). However, according to our knowledge, no other study has used this test.

Mannion et al. conducted a very interesting study to determine whether the twitch superimposition technique could be used to predict maximum force (isometric lifting test) of the spinal muscles from submaximal efforts (Mannion et al., 1997b). Although they reported an excellent curvilinear relationship between twitch force and submaximal force being sustained, they observed that the predicted MVC (extrapolated from the relationship) underestimated the true strength by about 18%. Such difference might result partly from the difficulty in stimulating the spinal muscle mass as a whole. The authors concluded that another testing apparatus and/or subject's posture might result in a more accurate prediction of maximal force (Mannion et al., 1997b). However, no other studies have used the twitch superimposition technique to predict back muscle maximal force since then.

Surface electromyography (S-EMG) technique is sometimes considered as the best tool to assess objectively trunk extensors muscle function because it enables to investigate and compare simultaneously and specifically several back muscles. Furthermore, this technique can be used during a submaximal and time-limited effort in order to limit the influence of individual factors (motivation, fears, etc.). Therefore S-EMG coupled to the endurance field (Sorensen, etc.) and dynamometric (static or dynamic) tests previously described have been frequently used in the literature (Mannion et al., 1997a; Elfving et al., 2000; Koumantakis et al., 2001; Ng et al., 1997; Kankaanpaa et al., 2005; Demoulin et al., 2007). Some devices such as the Back Analysis System (NeuroMuscular Research Center, Boston University, Boston, USA) were even developed to standardize assessments of back muscle dysfunction (i.e. repeated isometric extensions at a given percentage of the MVC associated to S-EMG monitoring) (De Luca, 1993; Roy et al., 1995). The EMG power spectrum has been widely used to calculate the median frequency (MF), mean power frequency (MPF), as well as their rates of decline during prolonged exercise in order to reflect muscle fatigue (Vollestad, 1997). Several studies observed that EMG fatigue parameters recorded after a prespecified period (often 45-60 seconds) of a fatiguing task were significantly correlated to the parameters monitored at the end of the endurance test (van Dieen et al., 1998; Suter & Lindsay, 2001) as well as to the maximal holding time (Kankaanpaa et al., 1997; Mannion et al., 1997a; van Dieen et al., 1998; Dederling et al., 1999). Furthermore, EMG fatigue parameters could be a better predictor of low back disorder than the maximal holding time (Mannion et al., 1997a).

Though submaximal tests coupled to S-EMG have become very popular, the validity of the EMG submaximal endurance tests performed at a given percentage of the MVC can be questioned. Indeed, the intensity of effort during such tests depends on the factors (motivation, pain, fears, etc.) influencing the MVC test previously performed; the absence of difference in EMG parameters between healthy and patients with CLBP and the smaller decrease in power frequency (reflecting lower fatigue) found in the latter group in some studies could be explained by the underestimation of the patients MVC resulting in a lower load level (Elfving et al., 2003; Lariviere et al., 2003a; Kramer et al., 2005). In order to avoid such a bias and to limit the influence of the anthropometric variables, Larivière et al. recently proposed a promising assessment based on S-EMG monitoring during intermittent submaximal static contractions (6,5 seconds contraction / 1,5 second rest) performed in a non-commercial trunk dynamometer at a specific intensity (90 N.m) during 5 to 10 minutes

(Lariviere et al., 2008a; Lariviere et al., 2009). Their results based on healthy subjects suggest that the EMG indices used in the study could predict absolute endurance as well as strength with the use of a single intermittent and time-limited endurance test (Lariviere et al., 2008b).

Although S-EMG technique appears attractive, it presents some drawbacks. Indeed, EMG results are influenced by many factors including the type, size, and location of the electrodes, the impedance of the source and amplifier, the location of the motor points, the type of contraction, the temperature of the muscle and skin, the force produced by the contraction, the fiber composition, the blood flow and the fat layer thickness (De Luca, 1993). Whereas intra-session reproducibility of EMG parameters seems generally satisfactory (Ng & Richardson, 1996), inter-session and inter-operator reproducibility remains controversial (Peach et al., 1998; Elfving et al., 1999; Danneels et al., 2001). Furthermore, S-EMG might not reliably isolate the activity of the different back muscles (Stokes et al., 2003) and the interpretation of EMG measurements at an individual level remains impossible at the moment because of the considerable inter-individual variability (Elfving et al., 2000; Arnall et al., 2002), thereby limiting its diagnostic usefulness (Pullman et al., 2000; Lariviere et al., 2002). Finally, the absence of standardized EMG protocols prevents from performing several comparative studies.

4. Conclusions

As shown in this review, several methods have been used to assess trunk extensor muscle performance. Unfortunately there is not yet a consensus regarding the optimal test to be used and the present literature review does not enable such a test to be determined. Further studies about the clinimetric properties of the maximal effort tests as well as comparison studies between the various existing tests and tools are needed. Anyway, when using such tests, several methodological cautions are necessary in clinical practice (e.g. a familiarization period to the device and to the test, several trials authorized, etc.) in order to avoid a learning effect; furthermore, results interpretation should always be careful, especially in painful or fearful subjects considering the risk of underestimating the true muscle performance. Additional effort to develop a submaximal test remains essential. Although the S-EMG technique appears to be a key investigation tool for research because individual factors do not influence the outcomes, further investigations are necessary to make the measurement interpretation possible at an individual level.

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6. References

- Adams, M.A.; Mannion, A.F. & Dolan, P. (1999). Personal risk factors for first-time low back pain. *Spine*, Vol.24, No.23, pp. 2497-2505.
- Al-Obaidi, S.; Al-Zoabi, B.; Chowdhury, R. & Al-Shuwai, N. (2003). Fatigue susceptibility of the lumbar extensor muscles among smokers. *Physiotherapy*, Vol.89, No.4, pp. 238-248.

- Al-Obaidi, S.M.; Beattie, P.; Al-Zoabi, B. & Al-Wekeel, S. (2005). The relationship of anticipated pain and fear avoidance beliefs to outcome in patients with chronic low back pain who are not receiving workers' compensation. *Spine*, Vol.30, No.9, pp. 1051-1057.
- Alaranta, H.; Hurri, H.; Heliovaara, M.; Soukka, A. & Harju, R. (1994). Non-dynamometric trunk performance tests: reliability and normative data. *Scandinavian Journal of Rehabilitation Medicine*, Vol.26, No.4, pp. 211-215.
- Alaranta, H.; Luoto, S.; Heliovaara, M. & Hurri, H. (1995). Static back endurance and the risk of low-back pain. *Clinical Biomechanics*, Vol.10, No.6, pp. 323-324.
- Arab, A.M.; Salavati, M.; Ebrahimi, I. & Ebrahim Mousavi, M. (2007). Sensitivity, specificity and predictive value of the clinical trunk muscle endurance tests in low back pain. *Clinical Rehabilitation*, Vol.21, No.7, pp. 640-647.
- Arnall, F.A.; Koumantakis, G.A.; Oldham, J.A. & Cooper, R.G. (2002). Between-days reliability of electromyographic measures of paraspinal muscle fatigue at 40, 50 and 60% levels of maximal voluntary contractile force. *Clinical Rehabilitation*, Vol.16, No.7, pp. 761-771.
- Ayers, S. & Pollock, M. (1999). Isometric dynamometry, In: *Spinal rehabilitation*, D.E. Stude, (Ed.), 339-367, Appleton & Lange, Stamford Connecticut.
- Balague, F.; Bibbo, E.; Melot, C.; Szpalski, M.; Gunzburg, R. & Keller, T.S. (2010). The association between isoinertial trunk muscle performance and low back pain in male adolescents. *European Spine Journal*, Vol.19, No.4, pp. 624-632.
- Barker, K.L.; Shamley, D.R. & Jackson, D. (2004). Changes in the cross-sectional area of multifidus and psoas in patients with unilateral back pain: the relationship to pain and disability. *Spine*, Vol.29, No.22, pp. E515-519.
- Bayramoglu, M.; Akman, M.N.; Kilinc, S.; Cetin, N.; Yavuz, N. & Ozker, R. (2001). Isokinetic measurement of trunk muscle strength in women with chronic low-back pain. *American Journal of Physical Medicine and Rehabilitation*, Vol.80, No.9, pp. 650-655.
- Beimborn, D.S. & Morrissey, M.C. (1988). A review of the literature related to trunk muscle performance. *Spine*, Vol.13, No.6, pp. 655-660.
- Bendix, A.E.; Bendix, T.; Haestrup, C. & Busch, E. (1998). A prospective, randomized 5-year follow-up study of functional restoration in chronic low back pain patients. *European Spine Journal*, Vol.7, No.2, pp. 111-119.
- Biering-Sorensen, F. (1984). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine*, Vol.9, No.2, pp. 106-119.
- Byl, N. & Sadowski, S. (1993). Inter-site reliability of repeated isokinetic measurements: Cybex back systems including trunk rotation, trunk extension flexion and lift task. *Isokinetics and Exercise Science*, Vol.3, pp. 139-147.
- Cale-Benzoor, M.; Albert, M.S.; Grodin, A. & Woodruff, L.D. (1992). Isokinetic trunk muscle performance characteristics of classical ballet dancers. *Journal of Orthopaedic and Sports Physical Therapy*, Vol.15, No.2, pp. 99-106.
- Carpenter, D.M. & Nelson, B.W. (1999). Low back strengthening for the prevention and treatment of low back pain. *Medicine and Science in Sports and Exercise*, Vol.31, No.1, pp. 18-24.
- Cassisi, J.E.; Robinson, M.E.; O'conner, P. & Macmillan, M. (1993). Trunk strength and lumbar paraspinal muscle activity during isometric exercise in chronic low-back pain patients and controls. *Spine*, Vol.18, No.2, pp. 245-251.

- Champagne, A.; Descarreaux, M. & Lafond, D. (2008). Back and hip extensor muscles fatigue in healthy subjects: task-dependency effect of two variants of the Sorensen test. *European Spine Journal*, Vol.17, No.12, pp. 1721-1726.
- Champagne, A.; Descarreaux, M. & Lafond, D. (2009). Comparison between elderly and young males' lumbopelvic extensor muscle endurance assessed during a clinical isometric back extension test. *Journal of Manipulative and Physiological Therapeutics*, Vol.32, No.7, pp. 521-526.
- Cole, M.H. & Grimshaw, P.N. (2003). Low back pain and lifting: a review of epidemiology and aetiology. *Work*, Vol.21, No.2, pp. 173-184.
- Coorevits, P.; Danneels, L.; Cambier, D.; Ramon, H. & Vanderstraeten, G. (2008). Assessment of the validity of the Biering-Sorensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *Journal of Electromyography and Kinesiology*, Vol.18, No.6, pp. 997-1005.
- Corin, G.; Strutton, P.H. & McGregor, A.H. (2005). Establishment of a protocol to test fatigue of the trunk muscles. *British Journal of Sports Medicine*, Vol.39, No.10, pp. 731-735.
- Crombez, G.; Vervaeke, L.; Baeyens, F.; Lysens, R. & Eelen, P. (1996). Do pain expectancies cause pain in chronic low back patients? A clinical investigation. *Behaviour Research and Therapy*, Vol.34, No.11-12, pp. 919-925.
- Crossman, K.; Mahon, M.; Watson, P.J.; Oldham, J.A. & Cooper, R.G. (2004). Chronic low back pain-associated paraspinal muscle dysfunction is not the result of a constitutionally determined "adverse" fiber-type composition. *Spine*, Vol.29, No.6, pp. 628-634.
- Crowther, A.; McGregor, A. & Strutton, P. (2007). Testing isometric fatigue in the trunk muscles. *Isokinetics and Exercise Science*, Vol.15, pp. 91-97.
- Da Silva, R.A.; Arsenault, A.B.; Gravel, D.; Lariviere, C. & De Oliveira, E. (2005). Back muscle strength and fatigue in healthy and chronic low back pain subjects: a comparative study of 3 assessment protocols. *Archives of Physical Medicine and Rehabilitation*, Vol.86, No.4, pp. 722-729.
- Daniels, K. & Denner, A. (1999). Analysis based medical training therapy for the spine (FPZ concept): quality assurance in the scope of evidence-based medicine. *Zeitschrift für Ärztliche Fortbildung und Qualitätssicherung*, Vol.93, No.5, pp. IV-V.
- Danneels, L.A.; Vanderstraeten, G.G.; Cambier, D.C.; Witvrouw, E.E. & De Cuyper, H.J. (2000). CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. *European Spine Journal*, Vol.9, No.4, pp. 266-272.
- Danneels, L.A.; Cagnie, B.J.; Cools, A.M.; Vanderstraeten, G.G.; Cambier, D.C.; Witvrouw, E.E. & De Cuyper, H.J. (2001). Intra-operator and inter-operator reliability of surface electromyography in the clinical evaluation of back muscles. *Manual Therapy*, Vol.6, No.3, pp. 145-153.
- De Luca, C.J. (1993). Use of the surface EMG signal for performance evaluation of back muscles. *Muscle Nerve*, Vol.16, No.2, pp. 210-216.
- Dedering, A.; Nemeth, G. & Harms-Ringdahl, K. (1999). Correlation between electromyographic spectral changes and subjective assessment of lumbar muscle fatigue in subjects without pain from the lower back. *Clinical Biomechanics*, Vol.14, No.2, pp. 103-111.
- Delitto, A.; Rose, S.J.; Crandell, C.E. & Strube, M.J. (1991). Reliability of isokinetic measurements of trunk muscle performance. *Spine*, Vol.16, No.7, pp. 800-803.
- Demoulin, C.; Grosdent, S.; Debois, I.; Mahieu, G.; Maquet, D.; Jidovstev, B.; Croisier, J.; Crielaard, J. & Vanderthommen, M. (2006a). Inter-session, inter-rater and inter-site

- reproducibility of isometric trunk muscle strength measurements. *Isokinetics and Exercise Science*, Vol.14, pp. 317-325.
- Demoulin, C.; Vanderthommen, M.; Duysens, C. & Crielaard, J.M. (2006b). Spinal muscle evaluation using the Sorensen test: a critical appraisal of the literature. *Joint Bone Spine*, Vol.73, No.1, pp. 43-50.
- Demoulin, C.; Crielaard, J.M. & Vanderthommen, M. (2007). Spinal muscle evaluation in healthy individuals and low-back-pain patients: a literature review. *Joint Bone Spine*, Vol.74, No.1, pp. 9-13.
- Demoulin, C. (2008). Contribution à l'évaluation et à la rééducation de la fonction musculaire du sujet lombalgique chronique. PhD Thesis, 192 pages. Département des Sciences de la Motricité, Université de Liège (ULg), Liège, Belgique.
- Demoulin, C.; Koninckx, S.; Mahieu, G.; Feiereisen, P.; Koch, D.; Crielaard, J.-M. & Vanderthommen, M. (2008a). Analyse corrélative des résultats de différents dynamomètres spécifiques pour l'évaluation des muscles du tronc *Revue du Rhumatisme*, Vol.75, No.10-11, pp. 1180.
- Demoulin, C.; Sac, D.; Serre, L.; Maquet, D.; Crielaard, J. & Vanderthommen, M. (2008b). Reproducibility and suitability of clinical assessments of trunk flexor and extensor muscles. *Journal of Musculoskeletal Pain*, Vol.16, pp. 301-311.
- Demoulin, C.; Grosdent, S.; Bury, T.; Croisier, J.-L.; Maquet, D.; Lehance, C.; Crielaard, J.M. & Vanderthommen, M. (2009). Cardiovascular responses to static assessments of trunk muscles. *Journal of Musculoskeletal Pain*, Vol.17, No.4, pp. 378-389.
- Demoulin, C.; Grosdent, S.; Capron, L.; Tomasella, M.; Somville, P.R.; Crielaard, J.M. & Vanderthommen, M. (2010). Effectiveness of a semi-intensive multidisciplinary outpatient rehabilitation program in chronic low back pain. *Joint Bone Spine*, Vol.77, No.1, pp. 58-63.
- Denner, A. (1997). *Muskuläre Profile der Wirbelsäule*, Springer, Berlin.
- Dillard, J., Trafimow, J.; Andersson, G.B. & Cronin, K. (1991). Motion of the lumbar spine. Reliability of two measurement techniques. *Spine*, Vol.16, No.3, pp. 321-324.
- Durmus, D.; Akyol, Y.; Alayli, G.; Tander, B.; Zahiroglu, Y. & Canturk, F. (2009). Effects of electrical stimulation program on trunk muscle strength, functional capacity, quality of life, and depression in the patients with low back pain: a randomized controlled trial. *Rheumatology International*, Vol.29, No.8, pp. 947-954.
- Dvir, Z. & Keating, J. (2001). Reproducibility and validity of a new test protocol for measuring isokinetic trunk extension strength. *Clinical Biomechanics*, Vol.16, No.7, pp. 627-630.
- Elfving, B.; Nemeth, G.; Arvidsson, I. & Lamontagne, M. (1999). Reliability of EMG spectral parameters in repeated measurements of back muscle fatigue. *Journal of Electromyography and Kinesiology*, Vol.9, No.4, pp. 235-243.
- Elfving, B.; Nemeth, G. & Arvidsson, I. (2000). Back muscle fatigue in healthy men and women studied by electromyography spectral parameters and subjective ratings. *Scandinavian Journal of Rehabilitation Medicine*, Vol.32, No.3, pp. 117-123.
- Elfving, B.; Dederig, A. & Nemeth, G. (2003). Lumbar muscle fatigue and recovery in patients with long-term low-back trouble--electromyography and health-related factors. *Clinical Biomechanics*, Vol.18, No.7, pp. 619-630.
- Enoka, R.M. & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *Journal of Physiology*, Vol.586, No.1, pp. 11-23.

- Essendrop, M.; Maul, I.; Laubli, T.; Riihimaki, H. & Schibye, B. (2002). Measures of low back function: a review of reproducibility studies. *Clinical Biomechanics*, Vol.17, No.4, pp. 235-249.
- Findley, B.; Brown, L.; Whitehurst, M.; Gilbert, R.; Groo, D. & O'neal, J. (2000). Sitting versus standing isokinetic trunk extension and flexion performance differences. *Journal of Strength and Conditioning Research*, Vol.14, No.3, pp. 310-315.
- Genty, M. & Schmidt, D. (2001). Utilisation de l'isocinétisme dans les programmes de rééducation du rachis (modalités pratiques, protocoles proposés), In: *Isocinétisme et rachis*, P. Codine, C. Hérisson, B. Denat, (Eds), 99-106, Masson, Paris.
- Gibbons, L.E.; Latikka, P.; Videman, T.; Manninen, H. & Battie, M.C. (1997a). The association of trunk muscle cross-sectional area and magnetic resonance image parameters with isokinetic and psychophysical lifting strength and static back muscle endurance in men. *Journal of Spinal Disorders*, Vol.10, No.5, pp. 398-403.
- Gibbons, L.E.; Videman, T. & Battie, M.C. (1997b). Isokinetic and psychophysical lifting strength, static back muscle endurance, and magnetic resonance imaging of the paraspinal muscles as predictors of low back pain in men. *Scandinavian Journal of Rehabilitation Medicine*, Vol.29, No.3, pp. 187-191.
- Giemza, C.; Bodnar, A.; Kabala, T.; Gruszecka, D.; Lipnicki, W.; Magiera, P. & Kowalski, J. (2006). The efficiency assessment of rehabilitation with DBC method in low back pain patients. *Ortopedia Traumatologia Rehabilitacja*, Vol.8, No.6, pp. 650-657.
- Gomez, T.; Beach, G.; Cooke, C.; Hrudey, W. & Goyert, P. (1991). Normative database for trunk range of motion, strength, velocity, and endurance with the Isostation B-200 Lumbar Dynamometer. *Spine*, Vol.16, No.1, pp. 15-21.
- Grabiner, M.D.; Jeziorowski, J.J. & Divekar, A.D. (1990). Isokinetic measurements of trunk extension and flexion performance collected with the biodex clinical data station. *Journal of Orthopaedic and Sports Physical Therapy*, Vol.11, No.12, pp. 590-598.
- Graves, J.E.; Pollock, M.L.; Carpenter, D.M.; Leggett, S.H.; Jones, A.; Macmillan, M. & Fulton, M. (1990). Quantitative assessment of full range-of-motion isometric lumbar extension strength. *Spine*, Vol.15, No.4, pp. 289-294.
- Graves, J.E.; Webb, D.C.; Pollock, M.L.; Matkozich, J.; Leggett, S.H.; Carpenter, D.M.; Foster, D.N. & Cirulli, J. (1994). Pelvic stabilization during resistance training: its effect on the development of lumbar extension strength. *Archives of Physical Medicine and Rehabilitation*, Vol.75, No.2, pp. 210-215.
- Gronblad, M.; Hurri, H. & Kouri, J.P. (1997). Relationships between spinal mobility, physical performance tests, pain intensity and disability assessments in chronic low back pain patients. *Scandinavian Journal of Rehabilitation Medicine*, Vol.29, No.1, pp. 17-24.
- Gruther, W.; Wick, F.; Paul, B.; Leitner, C.; Posch, M.; Matzner, M.; Crevenna, R. & Ebenbichler, G. (2009). Diagnostic accuracy and reliability of muscle strength and endurance measurements in patients with chronic low back pain. *J Rehabil Med*, Vol.41, No.8, pp. 613-619.
- Hakkinen, A.; Kuukkanen, T.; Tarvainen, U. & Ylinen, J. (2003). Trunk muscle strength in flexion, extension, and axial rotation in patients managed with lumbar disc herniation surgery and in healthy control subjects. *Spine*, Vol.28, No.10, pp. 1068-1073.
- Hamberg-Van Reenen, H.H.; Ariens, G.A.; Blatter, B.M.; Twisk, J.W.; Van Mechelen, W. & Bongers, P.M. (2006). Physical capacity in relation to low back, neck, or shoulder pain in a working population. *Occupational and Environmental Medicine*, Vol.63, No.6, pp. 371-377.

- Handa, N.; Yamamoto, H.; Tani, T.; Kawakami, T. & Takemasa, R. (2000). The effect of trunk muscle exercises in patients over 40 years of age with chronic low back pain. *Journal of Orthopaedic Science*, Vol.5, No.3, pp. 210-216.
- Hansen, J.W. (1964). Postoperative Management in Lumbar Disc Protrusions. I. Indications, Method and Results. II. Follow-up on a Trained and an Untrained Group of Patients. *Acta Orthopaedica Scandinavica (Suppl)*, Vol.71, pp. 1-47.
- Hansson, T.H.; Bigos, S.J.; Wortley, M.K. & Spengler, D.M. (1984). The load on the lumbar spine during isometric strength testing. *Spine*, Vol.9, No.7, pp. 720-724.
- Hasue, M.; Fujiwara, M. & Kikuchi, S. (1980). A new method of quantitative measurement of abdominal and back muscle strength. *Spine*, Vol.5, No.2, pp. 143-148.
- Hides, J.A.; Richardson, C.A. & Jull, G.A. (1996). Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine*, Vol.21, No.23, pp. 2763-2769.
- Hillman, M.; Wright, A.; Rajaratnam, G.; Tennant, A. & Chamberlain, M.A. (1996). Prevalence of low back pain in the community: implications for service provision in Bradford, UK. *Journal of Epidemiology and Community Health*, Vol.50, No.3, pp. 347-352.
- Huijnen, I.P.; Verbunt, J.A.; Peters, M.L. & Seelen, H.A. (2010). Is physical functioning influenced by activity-related pain prediction and fear of movement in patients with subacute low back pain? *European Journal of Pain*, Vol.14, No.6, pp. 661-666.
- Hultman, G.; Nordin, M.; Saraste, H. & Ohlson, H. (1993). Body composition, endurance, strength, cross-sectional area, and density of MM erector spinae in men with and without low back pain. *Journal of Spinal Disorders*, Vol.6, No.2, pp. 114-123.
- Hupli, M.; Sainio, P.; Hurri, H. & Alaranta, H. (1997). Comparison of trunk strength measurements between two different isokinetic devices used at clinical settings. *Journal of Spinal Disorders*, Vol.10, No.5, pp. 391-397.
- Hutten, M.M. & Hermens, H.J. (1997). Reliability of lumbar dynamometry measurements in patients with chronic low back pain with test-retest measurements on different days. *European Spine Journal*, Vol.6, No.1, pp. 54-62.
- Ito, T.; Shirado, O.; Suzuki, H.; Takahashi, M.; Kaneda, K. & Strax, T.E. (1996). Lumbar trunk muscle endurance testing: an inexpensive alternative to a machine for evaluation. *Archives of Physical Medicine and Rehabilitation*, Vol.77, No.1, pp. 75-79.
- Jorgensen, K. (1997). Human trunk extensor muscles physiology and ergonomics. *Acta Physiologica Scandinavica (Suppl)*, Vol.637, pp. 1-58.
- Kankaanpaa, M.; Taimela, S.; Webber, C.L., Jr.; Airaksinen, O. & Hanninen, O. (1997). Lumbar paraspinal muscle fatigability in repetitive isoinertial loading: EMG spectral indices, Borg scale and endurance time. *European Journal of Applied Physiology and Occupational Physiology*, Vol.76, No.3, pp. 236-242.
- Kankaanpaa, M.; Laaksonen, D.; Taimela, S.; Kokko, S.M.; Airaksinen, O. & Hanninen, O. (1998a). Age, sex, and body mass index as determinants of back and hip extensor fatigue in the isometric Sorensen back endurance test. *Archives of Physical Medicine and Rehabilitation*, Vol.79, No.9, pp. 1069-1075.
- Kankaanpaa, M.; Taimela, S.; Laaksonen, D.; Hanninen, O. & Airaksinen, O. (1998b). Back and hip extensor fatigability in chronic low back pain patients and controls. *Archives of Physical Medicine and Rehabilitation*, Vol.79, No.4, pp. 412-417.
- Kankaanpaa, M.; Colier, W.N.; Taimela, S.; Anders, C.; Airaksinen, O.; Kokko-Aro, S.M. & Hanninen, O. (2005). Back extensor muscle oxygenation and fatigability in healthy

- subjects and low back pain patients during dynamic back extension exertion. *Pathophysiology*, Vol.12, No.4, pp. 267-273.
- Karatas, G.K.; Gogus, F. & Meray, J. (2002). Reliability of isokinetic trunk muscle strength measurement. *American Journal of Physical Medicine and Rehabilitation*, Vol.81, No.2, pp. 79-85.
- Keller, A.; Johansen, J.G.; Hellesnes, J. & Brox, J.I. (1999). Predictors of isokinetic back muscle strength in patients with low back pain. *Spine*, Vol.24, No.3, pp. 275-280.
- Keller, A.; Hellesnes, J. & Brox, J.I. (2001). Reliability of the isokinetic trunk extensor test, Biering-Sorensen test, and Astrand bicycle test: assessment of intraclass correlation coefficient and critical difference in patients with chronic low back pain and healthy individuals. *Spine*, Vol.26, No.7, pp. 771-777.
- Konrad, P.; Schmitz, K. & Denner, A. (2001). Neuromuscular Evaluation of Trunk-Training Exercises. *Journal of Athletic Training*, Vol.36, No.2, pp. 109-118.
- Koumantakis, G.A.; Arnall, F.; Cooper, R.G. & Oldham, J.A. (2001). Paraspinal muscle EMG fatigue testing with two methods in healthy volunteers. Reliability in the context of clinical applications. *Clinical Biomechanics*, Vol.16, No.3, pp. 263-266.
- Kramer, M.; Ebert, V.; Kinzl, L.; Dehner, C.; Elbel, M. & Hartwig, E. (2005). Surface electromyography of the paravertebral muscles in patients with chronic low back pain. *Archives of Physical Medicine and Rehabilitation*, Vol.86, No.1, pp. 31-36.
- Kujala, U.M.; Taimela, S.; Viljanen, T. ; Jutila, H. ; Viitasalo, J.T. ; Videman, T. & Battie, M.C. (1996). Physical loading and performance as predictors of back pain in healthy adults. A 5-year prospective study. *European Journal of Applied Physiology and Occupational Physiology*, Vol.73, No.5, pp. 452-458.
- Kumar, S.; Dufresne, R.M. & Van Schoor, T. (1995). Human trunk strength profile in flexion and extension. *Spine*, Vol.20, No.2, pp. 160-168.
- Lariviere, C.; Gagnon, D.; Gravel, D.; Arsenaault, A.B.; Dumas, J.; Goyette, M. & Loisel, P. (2001). A triaxial dynamometer to monitor lateral bending and axial rotation moments during static trunk extension efforts. *Clinical Biomechanics*, Vol.16, No.1, pp. 80-83.
- Lariviere, C.; Arsenaault, A.B.; Gravel, D. ; Gagnon, D. & Loisel, P. (2002). Evaluation of measurement strategies to increase the reliability of EMG indices to assess back muscle fatigue and recovery. *Journal of Electromyography and Kinesiology*, Vol.12, No.2, pp. 91-102.
- Lariviere, C.; Arsenaault, A.B.; Gravel, D. ; Gagnon, D. & Loisel, P. (2003a). Surface electromyography assessment of back muscle intrinsic properties. *Journal of Electromyography and Kinesiology*, Vol.13, No.4, pp. 305-318.
- Lariviere, C.; Gravel, D.; Gagnon, D. ; Arsenaault, A.B. ; Loisel, P. & Lepage, Y. (2003b). Back strength cannot be predicted accurately from anthropometric measures in subjects with and without chronic low back pain. *Clinical Biomechanics*, Vol.18, No.6, pp. 473-479.
- Lariviere, C.; Gravel, D.; Gagnon, D.; Gardiner, P.; Arsenaault, A.B. & Gaudreault, N. (2006). Gender influence on fatigability of back muscles during intermittent isometric contractions: a study of neuromuscular activation patterns. *Clinical Biomechanics*, Vol.21, No.9, pp. 893-904.
- Lariviere, C.; Gagnon, D.; Gravel, D. & Arsenaault, A.B. (2008a). The assessment of back muscle capacity using intermittent static contractions. Part I - Validity and reliability of electromyographic indices of fatigue. *Journal of Electromyography and Kinesiology*, Vol.18, No.6, pp. 1006-1019.

- Lariviere, C.; Gravel, D.; Gagnon, D. & Arsenault, A.B. (2008b). The assessment of back muscle capacity using intermittent static contractions. Part II: validity and reliability of biomechanical correlates of muscle fatigue. *Journal of Electromyography and Kinesiology*, Vol.18, No.6, pp. 1020-1031.
- Lariviere, C.; Gravel, D.; Gagnon, D. & Arsenault, A.B. (2009). Toward the development of predictive equations of back muscle capacity based on frequency- and temporal-domain electromyographic indices computed from intermittent static contractions. *Spine Journal*, Vol.9, No.1, pp. 87-95.
- Latikka, P.; Battie, M.C.; Videman, T. & Gibbons, L.E. (1995). Correlations of isokinetic and psychophysical back lift and static back extensor endurance tests in men. *Clinical Biomechanics*, Vol.10, No.6, pp. 325-330.
- Latimer, J.; Maher, C.G.; Refshauge, K. & Colaco, I. (1999). The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine*, Vol.24, No.20, pp. 2085-2090.
- Ljungquist, T.; Fransson, B.; Harms-Ringdahl, K.; Bjornham, A. & Nygren, A. (1999). A physiotherapy test package for assessing back and neck dysfunction--discriminative ability for patients versus healthy control subjects. *Physiotherapy Research International*, Vol.4, No.2, pp. 123-140.
- Malliou, P.; Gioftsidou, A.; Beneka, A. & Godolias, G. (2006). Measurements and evaluations in low back pain patients. *Scandinavian Journal of Medicine and Science in Sports*, Vol.16, No.4, pp. 219-230.
- Manniche, C.; Hesselsoe, G.; Bentzen, L.; Christensen, I. & Lundberg, E. (1988). Clinical trial of intensive muscle training for chronic low back pain. *Lancet*, Vol.2, No.8626-8627, pp. 1473-1476.
- Mannion, A.F. & Dolan, P. (1994). Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue. *Spine*, Vol.19, No.11, pp. 1223-1229.
- Mannion, A.F.; Connolly, B.; Wood, K. & Dolan, P. (1997a). The use of surface EMG power spectral analysis in the evaluation of back muscle function. *Journal of Rehabilitation Research and Development*, Vol.34, No.4, pp. 427-439.
- Mannion, A.F.; Dolan, P.; Adam, G.G.; Adams, M.A. & Cooper, R.G. (1997b). Can maximal back muscle strength be predicted from submaximal efforts ? *Journal of Back and Musculoskeletal Rehabilitation*, Vol.9, No.1, pp. 49-51.
- Mannion, A.F.; Adams, M.A.; Cooper, R.G. & Dolan, P. (1999a). Prediction of maximal back muscle strength from indices of body mass and fat-free body mass. *Rheumatology*, Vol.38, No.7, pp. 652-655.
- Mannion, A.F.; Muntener, M.; Taimela, S. & Dvorak, J. (1999b). A randomized clinical trial of three active therapies for chronic low back pain. *Spine*, Vol.24, No.23, pp. 2435-2448.
- Mannion, A.F.; Dvorak, J.; Taimela, S. & Muntener, M. (2001). Increase in strength after active therapy in chronic low back pain (CLBP) patients: muscular adaptations and clinical relevance. *Schmerz*, Vol.15, No.6, pp. 468-473.
- Mayer, J.M.; Graves, J.E.; Robertson, V.L.; Pierra, E.A.; Verna, J.L. & Ploutz-Snyder, L.L. (1999). Electromyographic activity of the lumbar extensor muscles: effect of angle and hand position during Roman chair exercise. *Archives of Physical Medicine and Rehabilitation*, Vol.80, No.7, pp. 751-755.
- Mayer, T.; Gatchel, R.; Betancur, J. & Bovasso, E. (1995). Trunk muscle endurance measurement. Isometric contrasted to isokinetic testing in normal subjects. *Spine*, Vol.20, No.8, pp. 920-927.

- McGill, S.M.; Childs, A. & Liebenson, C. (1999). Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Archives of Physical Medicine and Rehabilitation*, Vol.80, No.8, pp. 941-944.
- McGregor, A.; Hill, A. & Grewar, J. (2004). Trunk strength patterns in elite rowers. *Isokinetics and Exercise Science*, Vol.12, pp. 253-261.
- McIntosh, G.; Wilson, L.; Affieck, M. & Hall, H. (1998). Trunk and lower extremity muscle endurance: normative data for adults. *Journal of Rehabilitation Outcome Measurement*, Vol.2, pp. 20-39.
- Menard, M.R.; Cooke, C.; Locke, S.R.; Beach, G.N. & Butler, T.B. (1994). Pattern of performance in workers with low back pain during a comprehensive motor performance evaluation. *Spine*, Vol.19, No.12, pp. 1359-1366.
- Mooney, V.; Kron, M.; Rummerfield, P. & Holmes, B. (1995). The effect of workplace based strengthening on low back injury rates: a case study in the strip mining industry. *Journal of Occupational Rehabilitation*, Vol.5, No.3, pp. 157-167.
- Moreau, C.E.; Green, B.N.; Johnson, C.D. & Moreau, S.R. (2001). Isometric back extension endurance tests: a review of the literature. *Journal of Manipulative and Physiological Therapeutics*, Vol.24, No.2, pp. 110-122.
- Moreland, J.; Finch, E.; Stratford, P.; Balsor, B. & Gill, C. (1997). Interrater reliability of six tests of trunk muscle function and endurance. *Journal of Orthopaedic and Sports Physical Therapy*, Vol.26, No.4, pp. 200-208.
- Morini, S.; Ciccarelli, A.; Cerulli, C.; Giombini, A.; Di Cesare, A. & Ripani, M. (2008). Functional anatomy of trunk flexion-extension in isokinetic exercise: muscle activity in standing and seated positions. *Journal of Sports Medicine and Physical Fitness*, Vol.48, No.1, pp. 17-23.
- Morlock, M.M.; Bonin, V.; Muller, G. & Schneider, E. (1997). Trunk muscle fatigue and associated EMG changes during a dynamic iso-inertial test. *European Journal of Applied Physiology and Occupational Physiology*, Vol.76, No.1, pp. 75-80.
- Muller, R.; Strassle, K. & Wirth, B. (2010). Isometric back muscle endurance: an EMG study on the criterion validity of the Ito test. *Journal of Electromyography and Kinesiology*, Vol.20, No.5, pp. 845-850.
- Nachemson, A.; Waddell, G. & Norlund, A. (2000). Epidemiology of neck and low back pain. In: *Neck and back pain: The scientific evidence of causes, diagnosis and treatment*, A. Nachemson, (Ed), 165-188, Lippincott Williams & Wilkins, Philadelphia.
- Nelson, B.W.; O'reilly, E.; Miller, M.; Hogan, M.; Wegner, J.A. & Kelly, C. (1995). The clinical effects of intensive, specific exercise on chronic low back pain: a controlled study of 895 consecutive patients with 1-year follow up. *Orthopedics*, Vol.18, No.10, pp. 971-981.
- Newton, M.; Thow, M.; Somerville, D.; Henderson, I. & Waddell, G. (1993). Trunk strength testing with iso-machines. Part 2: Experimental evaluation of the Cybex II Back Testing System in normal subjects and patients with chronic low back pain. *Spine*, Vol.18, No.7, pp. 812-824.
- Newton, M. & Waddell, G. (1993). Trunk strength testing with iso-machines. Part 1: Review of a decade of scientific evidence. *Spine*, Vol.18, No.7, pp. 801-811.
- Ng, J.K. & Richardson, C.A. (1996). Reliability of electromyographic power spectral analysis of back muscle endurance in healthy subjects. *Archives of Physical Medicine and Rehabilitation*, Vol.77, No.3, pp. 259-264.

- Ng, J.K.; Richardson, C.A. & Jull, G.A. (1997). Electromyographic amplitude and frequency changes in the iliocostalis lumborum and multifidus muscles during a trunk holding test. *Physical Therapy*, Vol.77, No.9, pp. 954-961.
- Nicolaisen, T. & Jorgensen, K. (1985). Trunk strength, back muscle endurance and low-back trouble. *Scandinavian Journal of Rehabilitation Medicine*, Vol.17, No.3, pp. 121-127.
- Parkkola, R.; Rytokoski, U. & Kormano, M. (1993). Magnetic resonance imaging of the discs and trunk muscles in patients with chronic low back pain and healthy control subjects. *Spine*, Vol.18, No.7, pp. 830-836.
- Parnianpour, M.; Nordin, M.; Kahanovitz, N. & Frankel, V. (1988). 1988 Volvo award in biomechanics. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. *Spine*, Vol.13, No.9, pp. 982-992.
- Parnianpour, M.; Li, F.; Nordin, M. & Frankel, V.H. (1989a). Reproducibility of trunk isoinertial performances in the sagittal, coronal, and transverse planes. *Bulletin of the Hospital for Joint Diseases Orthopaedic Institute*, Vol.49, No.2, pp. 148-154.
- Parnianpour, M.; Li, F.; Nordin, M. & Kahanovitz, N. (1989b). A database of isoinertial trunk strength tests against three resistance levels in sagittal, frontal, and transverse planes in normal male subjects. *Spine*, Vol.14, No.4, pp. 409-411.
- Peach, J.P.; Gunning, J. & McGill, S.M. (1998). Reliability of spectral EMG parameters of healthy back extensors during submaximum isometric fatiguing contractions and recovery. *Journal of Electromyography and Kinesiology*, Vol.8, No.6, pp. 403-410.
- Peel, C. & Alland, M.J. (1990). Cardiovascular responses to isokinetic trunk exercise. *Physical Therapy*, Vol.70, No.8, pp. 503-510.
- Picavet, H.S. & Schouten, J.S. (2003). Musculoskeletal pain in the Netherlands: prevalences, consequences and risk groups, the DMC(3)-study. *Pain*, Vol.102, No.1-2, pp. 167-178.
- Plamondon, A.; Marceau, C.; Stainton, S. & Desjardins, P. (1999). Toward a better prescription of the prone back extension exercise to strengthen the back muscles. *Scandinavian Journal of Medicine and Science in Sports*, Vol.9, No.4, pp. 226-232.
- Plamondon, A.; Serresse, O.; Boyd, K.; Ladouceur, D. & Desjardins, P. (2002). Estimated moments at L5/S1 level and muscular activation of back extensors for six prone back extension exercises in healthy individuals. *Scandinavian Journal of Medicine and Science in Sports*, Vol.12, No.2, pp. 81-89.
- Plamondon, A.; Trimble, K.; Lariviere, C. & Desjardins, P. (2004). Back muscle fatigue during intermittent prone back extension exercise. *Scandinavian Journal of Medicine and Science in Sports*, Vol.14, No.4, pp. 221-230.
- Pollock, M.; Graves, J.; Leggett, S.; Young, G.; Garzarella, L.; Carpenter, D.; Fulton, M. & Jones, A. (1991). Accuracy of counter weighting to account for upper body mass in testing lumbar extension strength. *Medicine and Science in Sports and Exercise*, Vol.23, No.4, pp. S66.
- Pullman, S.L.; Goodin, D.S.; Marquinez, A.I.; Tabbal, S. & Rubin, M. (2000). Clinical utility of surface EMG: report of the therapeutics and technology assessment subcommittee of the American Academy of Neurology. *Neurology*, Vol.55, No.2, pp. 171-177.
- Rainville, J.; Hartigan, C.; Jouve, C. & Martinez, E. (2004). The influence of intense exercise-based physical therapy program on back pain anticipated before and induced by physical activities. *Spine Journal*, Vol.4, No.2, pp. 176-183.
- Rantanen, P.; Penttinen, E.; Rinta-Kaupilla, S. & Ruusila, T. (1995). Cardiovascular stress in isokinetic trunk strength test. *Spine*, Vol.20, No.4, pp. 485-488.

- Rantanen, T.; Era, P. & Heikkinen, E. (1997). Physical activity and the changes in maximal isometric strength in men and women from the age of 75 to 80 years. *Journal of the American Geriatrics Society*, Vol.45, No.12, pp. 1439-1445.
- Rashiq, S.; Koller, M.; Haykowsky, M. & Jamieson, K. (2003). The effect of opioid analgesia on exercise test performance in chronic low back pain. *Pain*, Vol.106, No.1-2, pp. 119-125.
- Raty, H.P.; Kujala, U.; Videman, T.; Koskinen, S.K.; Karppi, S.L. & Sarna, S. (1999). Associations of isometric and isoinertial trunk muscle strength measurements and lumbar paraspinal muscle cross-sectional areas. *Journal of Spinal Disorders*, Vol.12, No.3, pp. 266-270.
- Reid, S.; Hazard, R.G. & Fenwick, J.W. (1991). Isokinetic trunk-strength deficits in people with and without low-back pain: a comparative study with consideration of effort. *Journal of Spinal Disorders*, Vol.4, No.1, pp. 68-72.
- Robinson, M.E.; Greene, A.F.; O'connor, P.; Graves, J.E. & Macmillan, M. (1992). Reliability of lumbar isometric torque in patients with chronic low back pain. *Physical Therapy*, Vol.72, No.3, pp. 186-190.
- Ropponen, A.; Gibbons, L.E.; Videman, T. & Battie, M.C. (2005). Isometric back extension endurance testing: reasons for test termination. *Journal of Orthopaedic and Sports Physical Therapy*, Vol.35, No.7, pp. 437-442.
- Ropponen, A. (2006). Comparison of the roles of common constitutional and behavioural parameters in back performance estimates. *Isokinetics and Exercise Science*, Vol.14, pp. 241-250.
- Roussel, N.A.; Truijen, S.; De Kerf, I.; Lambeets, D.; Nijs, J. & Stassijns, G. (2008). Reliability of the assessment of lumbar range of motion and maximal isometric strength in patients with chronic low back pain. *Archives of Physical Medicine and Rehabilitation*, Vol.89, No.4, pp. 788-791.
- Roy, S.H.; De Luca, C.J.; Emley, M. & Buijs, R.J. (1995). Spectral electromyographic assessment of back muscles in patients with low back pain undergoing rehabilitation. *Spine*, Vol.20, No.1, pp. 38-48.
- Rytokoski, U.; Karppi, S.L.; Puukka, P.; Soini, J. & Ronnema, T. (1994). Measurement of low back mobility, isometric strength and isoinertial performance with isostation B-200 triaxial dynamometer: reproducibility of measurement and development of functional indices. *Journal of Spinal Disorders*, Vol.7, No.1, pp. 54-61.
- Sachs, B.L.; Ahmad, S.S.; Lacroix, M.; Olimpico, D.; Heath, R.; David, J.A. & Scala, A.D. (1994). Objective assessment for exercise treatment on the B-200 isostation as part of work tolerance rehabilitation. A random prospective blind evaluation with comparison control population. *Spine*, Vol.19, No.1, pp. 49-52.
- Salminen, J.J.; Maki, P.; Oksanen, A. & Pentti, J. (1992). Spinal mobility and trunk muscle strength in 15-year-old schoolchildren with and without low-back pain. *Spine*, Vol.17, No.4, pp. 405-411.
- Salminen, J.J.; Erkintalo, M.; Laine, M. & Pentti, J. (1995). Low back pain in the young. A prospective three-year follow-up study of subjects with and without low back pain. *Spine*, Vol.20, No.19, pp. 2101-2108.
- San Juan, J.G.; Yaggie, J.A.; Levy, S.S.; Mooney, V.; Udermann, B.E. & Mayer, J.M. (2005). Effects of pelvic stabilization on lumbar muscle activity during dynamic exercise. *Journal of Strength and Conditioning Research*, Vol.19, No.4, pp. 903-907.

- Schenk, P.; Klipstein, A.; Spillmann, S.; Stroyer, J. & Laubli, T. (2006). The role of back muscle endurance, maximum force, balance and trunk rotation control regarding lifting capacity. *European Journal of Applied Physiology*, Vol.96, No.2, pp. 146-156.
- Shirado, O.; Kaneda, K. & Ito, T. (1992). Trunk-muscle strength during concentric and eccentric contraction: a comparison between healthy subjects and patients with chronic low-back pain. *Journal of Spinal Disorders*, Vol.5, No.2, pp. 175-182.
- Shirado, O.; Ito, T.; Kaneda, K. & Strax, T.E. (1995a). Concentric and eccentric strength of trunk muscles: influence of test postures on strength and characteristics of patients with chronic low-back pain. *Archives of Physical Medicine and Rehabilitation*, Vol.76, No.7, pp. 604-611.
- Shirado, O.; Ito, T.; Kaneda, K. & Strax, T.E. (1995b). Electromyographic analysis of four techniques for isometric trunk muscle exercises. *Archives of Physical Medicine and Rehabilitation*, Vol.76, No.3, pp. 225-229.
- Simmonds, M.J.; Olson, S.L.; Jones, S.; Hussein, T.; Lee, C.E.; Novy, D. & Radwan, H. (1998). Psychometric characteristics and clinical usefulness of physical performance tests in patients with low back pain. *Spine*, Vol.23, No.22, pp. 2412-2421.
- Sjolie, A.N. & Ljunggren, A.E. (2001). The significance of high lumbar mobility and low lumbar strength for current and future low back pain in adolescents. *Spine*, Vol.26, No.23, pp. 2629-2636.
- Smeets, R.J. & Wittink, H. (2007). The deconditioning paradigm for chronic low back pain unmasked? *Pain*, Vol.130, No.3, pp. 201-202.
- Smeets, R.J.; Vlaeyen, J.W.; Hidding, A.; Kester, A.D.; Van Der Heijden, G.J. & Knottnerus, J.A. (2008). Chronic low back pain: physical training, graded activity with problem solving training, or both? The one-year post-treatment results of a randomized controlled trial. *Pain*, Vol.134, No.3, pp. 263-276.
- Smith, D.; Bruce-Low, S. & Bissell, G. (2008). Twenty years of specific, isolated lumbar extension research: a review. *Journal of Orthopaedics*, Vol.5, No.1, pp. e14.
- Stokes, I.A.; Henry, S.M. & Single, R.M. (2003). Surface EMG electrodes do not accurately record from lumbar multifidus muscles. *Clinical Biomechanics*, Vol.18, No.1, pp. 9-13.
- Suni, J.H.; Miilunpalo, S.I.; Asikainen, T.M.; Laukkanen, R.T.; Oja, P.; Pasanen, M.E.; Bos, K. & Vuori, I.M. (1998). Safety and feasibility of a health-related fitness test battery for adults. *Physical Therapy*, Vol.78, No.2, pp. 134-148.
- Suter, E. & Lindsay, D. (2001). Back muscle fatigability is associated with knee extensor inhibition in subjects with low back pain. *Spine*, Vol.26, No.16, pp. E361-366.
- Swezey, R.L.; Swezey, A. & Adams, J. (2000). Isometric progressive resistive exercise for osteoporosis. *Journal of Rheumatology*, Vol.27, No.5, pp. 1260-1264.
- Szpalski, M.; Federspiel, C.F.; Poty, S.; Hayez, J.P. & Debaize, J.P. (1992). Reproducibility of trunk isoinertial dynamic performance in patients with low back pain. *Journal of Spinal Disorders*, Vol.5, No.1, pp. 78-85.
- Taimela, S. & Harkapaa, K. (1996). Strength, mobility, their changes, and pain reduction in active functional restoration for chronic low back disorders. *Journal of Spinal Disorders*, Vol.9, No.4, pp. 306-312.
- Taimela, S.; Kankaanpaa, M. & Airaksinen, O. (1998). A submaximal back extension endurance test utilising subjective perception of low back fatigue. *Scandinavian Journal of Rehabilitation Medicine*, Vol.30, No.2, pp. 107-112.
- Takemasa, R.; Yamamoto, H. & Tani, T. (1995). Trunk muscle strength in and effect of trunk muscle exercises for patients with chronic low back pain. The differences in patients with and without organic lumbar lesions. *Spine*, Vol.20, No.23, pp. 2522-2530.

- Tekin, Y.; Ortancil, O.; Ankarali, H.; Basaran, A.; Sarikaya, S. & Ozdolap, S. (2009). Biering-Sorensen test scores in coal miners. *Joint Bone Spine*, Vol.76, No.3, pp. 281-285.
- Thomas, J.S.; France, C.R.; Sha, D. & Wiele, N.V. (2008). The influence of pain-related fear on peak muscle activity and force generation during maximal isometric trunk exertions. *Spine*, Vol.33, No.11, pp. E342-348.
- Udermann, B.E.; Graves, J.E.; Donelson, R.G.; Ploutz-Snyder, L.; Boucher, J.P. & Iriso, J.H. (1999). Pelvic restraint effect on lumbar gluteal and hamstring muscle electromyographic activation. *Archives of Physical Medicine and Rehabilitation*, Vol.80, No.4, pp. 428-431.
- Udermann, B.E.; Mayer, J.M.; Graves, J.E. & Murray, S.R. (2003). Quantitative Assessment of Lumbar Paraspinal Muscle Endurance. *Journal of Athletic Training*, Vol.38, No.3, pp. 259-262.
- Van Dieen, J.H.; Heijblom, P. & Bunkens, H. (1998). Extrapolation of time series of EMG power spectrum parameters in isometric endurance tests of trunk extensor muscles. *Journal of Electromyography and Kinesiology*, Vol.8, No.1, pp. 35-44.
- Vanderthommen, M.; Demoulin, C.; Jacques, P.-A. & Crielaard, J.-M. (2007). Muscular recruitment during instrumental evaluation of the trunk extension torque: influence of a pelvic stabilization system, In: *6th Interdisciplinary World Congress on Low Back & Pelvic Pain*, 350-351, Abstract book (poster), Barcelona, Spain.
- Verbunt, J.A.; Seelen, H.A.; Vlaeyen, J.W.; Van De Heijden, G.J.; Heuts, P.H.; Pons, K. & Knottnerus, J.A. (2003). Disuse and deconditioning in chronic low back pain: concepts and hypotheses on contributing mechanisms. *European Journal of Pain* Vol.7, No.1, pp. 9-21.
- Verbunt, J.A.; Seelen, H.A.; Vlaeyen, J.W.; Bousema, E.J.; Van Der Heijden, G.J.; Heuts, P.H. & Knottnerus, J.A. (2005). Pain-related factors contributing to muscle inhibition in patients with chronic low back pain: an experimental investigation based on superimposed electrical stimulation. *Clinical Journal of Pain*, Vol.21, No.3, pp. 232-240.
- Verbunt, J.A.; Smeets, R.J. & Wittink, H.M. (2010). Cause or effect? Deconditioning and chronic low back pain. *Pain*, Vol.149, No.3, pp. 428-430.
- Viljanen, T.; Viitasalo, J.T. & Kujala, U.M. (1991). Strength characteristics of a healthy urban adult population. *European Journal of Applied Physiology and Occupational Physiology*, Vol.63, No.1, pp. 43-47.
- Vlaeyen, J.W.; Kole-Snijders, A.M.; Boeren, R.G. & Van Eek, H. (1995). Fear of movement/(re)injury in chronic low back pain and its relation to behavioral performance. *Pain*, Vol.62, No.3, pp. 363-372.
- Vollestad, N.K. (1997). Measurement of human muscle fatigue. *Journal of Neuroscience Methods*, Vol.74, No.2, pp. 219-227.
- Walsworth, M. (2004). Lumbar paraspinal electromyographic activity during trunk extension exercises on two types of exercise machines. *Electromyography and Clinical Neurophysiology*, Vol.44, No.4, pp. 201-207.
- Wang, M.; Leger, A.B. & Dumas, G.A. (2005). Prediction of back strength using anthropometric and strength measurements in healthy females. *Clinical Biomechanics*, Vol.20, No.7, pp. 685-692.