# Spinal exercise prescription in sport

Spencer, S; Wolf, Alexander; Rushton, Alison

Link to publication on Research at Birmingham portal

1 **Spinal exercise prescription in sport: classifying physical training and rehabilitation by intention**

2 **and outcome**

3

4 **Context:** Identification of strategies to prevent spinal injury, optimise rehabilitation, and enhance

5 performance is a priority for practitioners.  Different exercises produce different effects on

6 neuromuscular performance.  Clarity of the purpose of a prescribed exercise is central to

7 successful outcome.  There is a need to classify spinal exercises according to the objective of the

8 exercise and planned physical outcome.

9

10 **Objective:** The objectives of this study were to define the modifiable spinal abilities which

11 underpin optimal function during skilled athletic performance, and to classify spinal exercises

12 according to the objective of the exercise and intended physical outcomes.

13

14 **Design:** A qualitative consensus method of 4 iterative phases. 1] Exploratory panel carried out an

15 extended review the literature to identify key themes and sub themes to inform the definition of

16 physical abilities, exercise categories and physical outcomes. 2] Expert project group reviewed

17 panel findings. 3] Draft classification discussed with physiotherapists (n=49), and international

18 experts. 4] Revised classification reviewed by lead physiotherapy and strength & conditioning

19 teams (n=17). Consensus was defined as unanimous agreement.

20

21 **Results:** Spinal abilities were defined in four categories: mobility, motor control, work capacity,

22 and strength. Exercises were sub-classified by functionality as non-functional or functional; and by

23 spinal displacement as either static (neutral spinal posture with no segmental displacement) or

24 dynamic (dynamic segmental movement). The proposed terminology and classification supports

25 commonality of language for practitioners.

26

27 **Conclusions:** The Spinal Exercise Classification will support clinical reasoning through description

28 of a framework of spinal exercise objectives which clearly define the nature of exercise

29 prescription required to deliver intended physical outcomes.

30

31 **Key Words:** spine, back, exercise prescription, classification, training, rehabilitation

32

33

| Key Points |
| --- |
| • The spinal abilities underpinning optimal function during skilled athletic performance have been evaluated and a comprehensive framework of exercise and physical outcomes has been established. |
| • The framework provides a basis for clinical reasoning in spinal exercise prescription and establishes a platform for shared understanding to enable interdisciplinary working, applicable within a diverse spectrum of musculoskeletal practice. |

34

35

36

37

38

39

40

41

42

43

**INTRODUCTION**

Injury epidemiological data suggests that the prevalence of back pain in athletes is between 30-50%[1,2]. Injury surveillance data collected by The English Institute of Sport (EIS) between 2009-2012 across 11 Olympic sports indicated that thoracic and lumbar spine injury (LSI) accounted for 14.2% of all injuries and resulted in 737 days lost from training and competition (unpublished data). Injury was prevalent in sports which place significant demands on the spine through intensive and/or repetitive directional loading[3,4] including gymnastics, diving, weightlifting, cricket and rowing. Identification of strategies to prevent spinal injury, optimise spinal rehabilitation, and enhance spinal performance is a priority for practitioners.

Spinal function has been defined as the ability to create, absorb and transfer force and motion to the terminal appendicular segment during performance of skilled motor tasks[5]. Theoretical definitions of 'core stability' (CS) however, fail to represent the relationship between passive anatomical structure and the complex neuromuscular system coordination required to maintain spinal integrity under varying loads and motion demands. The nature of spinal integrity during sporting activity is therefore task specific. The theoretical basis of 'optimal' movement efficiency is therefore an expression of the co-ordinated interaction of numerous physical abilities underpinning spinal function[6].

Specificity of training enables the development of targeted outcome measures to enhance performance. During rehabilitation, practitioners must also consider the impact of pathology/pain on specific physical abilities and identify effective strategies to address dysfunction. The use of exercise is unequivocally accepted as part of a multifaceted approach to training and

68      rehabilitation[7]. Identification of sub optimal physical performance forms the basis of clinical

69      reasoning to inform exercise prescription.

70

71      Historically, the nature of spinal exercise prescription has been subject to widespread debate[8,9],

72      centred on the relative understanding and importance of CS; driven by its role in the management

73      of chronic low back pain[10]. Whilst significant progress in detailing the components of spinal

74      stability alongside its relationship with spinal mobility has been made[11], uni-dimensional

75      paradigms of exercise prescription persist. For example, approaches have attempted to isolate

76      groups of core muscles and/or their function, despite the importance of a synergistic contribution

77      of many different muscles in order to balance stability and movement demands[12]. Furthermore,

78      given that different exercises produce different effects on neuromuscular performance, use of the

79      term CS is problematic as it does not adequately define the intent of an exercise, and is often used

80      by practitioners when attempting to deliver several different training or rehabilitation outcomes.

81      As a consequence, spinal exercises (and often exercises in general) are frequently described by

82      name, equipment used, or place performed (e.g. Pilates/core exercises, mat exercises, gym

83      exercises), rather than by intent, loading and execution. Failure to delineate exercise intention

84      may also lead to miscommunication between practitioners. The objectives of this study were

85      twofold:

86

87      1. To define the modifiable spinal abilities which underpin optimal function during skilled athletic

88      performance and clarify the impact of spinal pain/pathology.

89

90      2. To classify spinal exercises according to the objective of the exercise and intended physical

91      outcomes to inform training and rehabilitation.

92

93 **METHODS**

94

95 Qualitative consensus method of 4 iterative phases (Figure 1). A conceptual framework was

96 defined to underpin the study methods (Figure 2). The framework forms an analytical tool that

97 was used in phase 1 to organise the ideas emerging from the literature. It provided a structure of

98 starting principles and assumptions that illustrate a broad concept.

99

100 *Phase 1*

101

102 An exploratory panel consisting of 2 senior physiotherapists and 2 senior strength and

103 conditioning coaches with significant experience in spinal training and rehabilitation in the EIS was

104 formed to carry out an extended review of the literature (Table 1) to: i) Identify modifiable spinal

105 abilities defining optimal function during skilled athletic performance; ii) clarify the impact of

106 spinal pain/pathology on specific physical abilities; and iii) define categories of exercise objectives

107 and physical outcomes. The literature search employed sensitive topic-based strategies designed

108 for each database. Search dates were from database inception to 31st July 2013 to inform phase 1.

109 The search has been recently updated to 31st July 2015 to reflect contemporary literature.

110

111 <u>Databases</u>

112 • CINAHL, EMBASE, and MEDLINE Databases

113 • Selected Internet sites and Indexes: PubMed

114

115 <u>Search strategy</u>

116 The search strategy included search terms informed by the conceptual framework. Specifically:

117     1] Anatomical and neuromuscular interactions in functional spinal control – Core, Stability (spinal),

118     Function (spinal),  Neuromuscular (control)  2] Spinal abilities defining optimal function during

119     skilled athletic performance – Mobility, Motor Control, Strength Endurance, Strength, Rate of

120     force development, Power,  Performance (Athletic / Sporting)  3] Impact of spinal pain/pathology –

121     Low back injury, Low back pain, Pathology (spine), Lumbar spine, Sport  4] Exercise specificity and

122     physical adaptation – Training, Injury prevention, Rehabilitation, Exercise, Outcome measures,

123     Physical/physiological adaptation.  Studies not written in English were excluded from the analysis,

124     but there were no restrictions on study design.  1614 studies were retrieved from the initial

125     searches.  Findings from studies were analysed in the context of any methodological limitations.

126     Key themes and sub themes (e.g. exercise objective grouping, sub-classification requirements)

127     were identified to inform the definition of physical abilities, exercise categories and physical

128     outcomes.

129

130     *Phase 2*

131

132     An expert project group was convened to review/revise the initial panel findings.  The group

133     consisted of 5 physiotherapists and 5 strength and conditioning coaches holding national

134     leadership positions within the EIS (Table 1), and regularly engaged in spinal training and

135     rehabilitation.  Independently they identified areas for discussion and review.  Collectively they

136     agreed modifications to the definition of physical abilities, exercise categories and physical

137     outcomes, and a draft classification was formulated, informed by the study's conceptual

138     framework.   An example of an area discussed and modified was the requirement for work

139     capacity and strength to be separated as two distinct physical performance parameters.

140

141     *Phase 3*

142

143 The draft classification was presented to all EIS physiotherapists (n=49) at a consensus forum, and

144 sent to key experts in the field for international expert review.  Data were analysed to inform

145 emerging themes and sub-themes that were subsequently integrated into a revised classification.

146 Examples of themes included understanding and managing practitioner bias, clarity of

147 presentation, and agreed terminology/use of language.

148

149 *Phase 4*

150

151 The classification was presented to members of the EIS technical lead physiotherapy and strength

152 and conditioning teams (n=17) for discussion.  Discussion focused around the strengths of the

153 framework and its potential application in elite sport.

154

155 *Definition of consensus*

156

157 Consensus was defined as unanimous agreement and this was achieved at each phase.   The

158 classification was accepted by unanimous agreement with minor amendments.  The results

159 section presents the definitive classification.

160

161

162 Figure 1: Flow diagram of consensus process.

163

164

165 Figure 2: Conceptual framework underpinning the study methods.

166

167

168    **Table 1: Exploratory panel and expert project group participant characteristics**

169

170

171    **RESULTS**

172

173    **Objective 1:**

174

175    **Identification of modifiable spinal abilities which underpin optimal function during skilled**

176    **athletic performance**

177

178    Spinal abilities can be defined in four distinct categories: mobility, motor control, work capacity

179    and strength[13-15 16]. It was important to consider the extent to which each category contributes to

180    spinal neuromuscular control[5], the impact of pain/pathology, and how exercise interventions are

181    utilised to influence targeted physical outcomes.  Modifiable spinal abilities which underpin

182    optimal function during skilled athletic performance are summarised in Figure 3 and defined in

183    Appendix 1 (for online publication).

184

185    *Mobility*

186

187    Mobility is defined as freedom of movement at spinal segments and provides the basis for the

188    development of motor control[17] and optimal spinal function[18].  Furthermore, the relationship

189    between axial mobility and athletic performance has been established[19,20].

190

8

191 Deficits in spinal movement have been identified in athletes with a history of low back pain (LBP)[21-

192 23], where changes in mobility are a product of the interaction between soft tissue and articular

193 dysfunction. It is plausible that abnormal movement patterns or repetitive directional loading

194 results in consistent absence of mechanical tension, associated with connective tissue remodelling

195 and eventual loss of muscle fibre length[24,25]. Loss of mobility could also represent ==an adaptive or==

196 ==maladaptive mechanism by which the body attempts to achieve active stability and maintain a==

197 ==level function in the presence of pain,== physical stress or failed motor control[26].

198

199 A myriad of therapeutic interventions are employed to influence neurophysical mechanisms

200 associated with loss of mobility (hypomobility) such as focal articular/tissue restriction, pain and

201 altered muscular tone[27]. Exercise is frequently utilised to influence spinal motion and mobility

202 exercises can also be performed in combination with limb movement to augment tissue

203 elongation throughout a continuous myofascial line[28]. Reliable assessment of spinal motion has

204 been established[29-32]; and effective restoration of spinal range of motion following flexibility

205 training has been demonstrated in the LBP population[33,34]. It should be noted that support for

206 inclusion of this component within the classification is primarily based on clinical concepts.

207

208 *Motor control*

209

210 Maintenance of spinal integrity during skilled movement tasks is not only dependent on muscular

211 capacity, but the ability to process sensory input, interpret the status of stability and motion, and

212 establish strategies to overcome predictable and unexpected movement challenges[35]. The spinal

213 stability required during athletic performance is task specific, governed by the nature of the

214 intended movement, the magnitude of imposed load and the perception of risk associated with

215 the activity[36]. The central nervous system therefore determines the requirements for stability and

216    co-ordinates contraction of deep and superficial core muscles using both feed-forward and

217    feedback control mechanisms[7,37]. In the presence of pain, the relationship between task demand

218    for stability and muscular recruitment becomes incoherent, resulting in delayed trunk muscle

219    reflex responses and excessive outer core muscular activation[38-40]. Classification systems have

220    been developed to establish the nature of adaptive motor responses in the presence of pain, and

221    identify maladaptive motor control impairments as a causative factor in spinal pain disorders[41,42].

222

223    Motor adaptation to pain has been demonstrated in athletes with LBP[43] and groin pain[44]; following

224    recovery from a recent episode of LBP[45]; and is observable in recurrent LBP patients during periods

225    of remission[46]. Furthermore, reflex response latencies can pre-exist within a healthy athletic

226    population, significantly increasing the risk of sustaining a LSI[47]. There is evidence to suggest that

227    motor adaptation to pain can be influenced through exercise-based intervention. Segmental

228    stabilisation exercises first described by Richardson and Jull (1995)[48] focus on retraining

229    coordinated co-contraction of the deep trunk muscles through simultaneous isometric co-

230    contraction of transversus abdominis (TrA) and multifidus in a static neutral spine position.

231    Exercise has been shown to be effective in restoring delayed/reduced activation of TrA[49] and

232    multifidus[50], with positive effects persisting after cessation of training[51]. Despite its scientific

233    foundation and widespread anecdotal support, impaired feed-forward activation of local

234    stabilisation muscles in LBP patients has been challenged[52]. Furthermore, evidence has also

235    questioned the ability to influence anticipatory muscle patterning following the performance of

236    segmental stabilisation exercises[53] aligned with the preferential impact on pain and dysfunction in

237    comparison to any other form of active exercise[54].

238

239    The ability to dissociate spinal and appendicular movement provides a static platform for force

240    absorption/transference and is a product of mobility/neuromuscular control of the limbs,

241 alongside the maintenance of a static neutral lumbar position. During sporting activities imparting

242 high loads through the spine, it is important that forces are evenly distributed to minimise loading

243 of vulnerable tissues in the spine[55, 56]. Inability to control a neutral position increases the potential

244 for tissue damage, especially during repetitive loading activities. Clinical tests have been shown to

245 reliably identify the performance of dissociation tasks under both low and high load conditions[57];

246 with movement control deficits identified in patients with LBP[58]. It is hypothesised that failed load

247 transfer during low load conditions is primarily due to inadequate motor skill competence or

248 altered mechanical behaviour associated with pain or the threat of pain or injury[59]. Failure under

249 higher loads may be attributed to other factors (e.g. insufficient muscular capacity), requiring

250 detailed assessment to establish the nature of the movement control loss.

251

252 During dynamic spinal movement, coordinated neuromuscular control of intersegmental

253 articulation is provided by precise coordination of surrounding musculature[60]. Proximal to distal

254 segmental sequencing is critical for the performance of skills which demand that maximum speed

255 is produced at the end of the distal segment in the kinetic chain, such as kicking or throwing[19].

256 Failed load transfer during segmental motion results in aberrant motor patterns, which could

257 hypothetically result in tissue damage through uneven load distribution and focal tissue stress [42,61].

258 Conversely, changes in motor control in some LBP subgroups have been associated with a

259 compromised ability to coordinate spinal motion (due to excessive aberrant muscular co-

260 contraction) resulting in an inability to perform controlled segmental movements[62]. Sequential

261 segmental control exercises (for instance dynamic pelvic-tilting) are intended to establish or

262 retrain appropriate muscular recruitment, co-ordinated dynamic motor control and proprioceptive

263 awareness[63].

264

265    Facilitation of skilled motor learning during rehabilitation requires autonomous engagement in the

266    learning process[64]. Once the subject is motivated to learn a new motor skill, it is important to

267    clearly detail the new task to be learned (e.g. through instruction, demonstration)[65]. In addition,

268    the process must provide neuromuscular challenge through progressive difficulty[66] and

269    variability[67], underpinned by regular deliberate practice[68] with appropriate knowledge of results

270    and performance related to the task[69].

271

272    *Work Capacity (WC)*

273

274    Work capacity (WC) is synonymous with local muscular endurance[70]. This can be defined as the

275    ability to produce or tolerate variable intensities and durations of work and contributes to the

276    ability of an athlete to perform efficiently in a given sport[70,71]. WC is a training outcome and not a

277    performance outcome test. The accumulation of training over many weeks and months results in

278    chronic local adaptation to muscle, tendon and metabolic biogenesis[72-79]. This chronic local

279    adaptation increases the ability of the system to produce more work during repeated efforts,

280    allows the local musculature to tolerate (or demonstrate resilience to) a larger training volume of

281    work[71] and supports the performance of work closer to the intensity and duration required for

282    sporting performance.

283

284    By comparison, strength endurance has been described as a performance outcome test

285    completed in isolation whereby the goal is to achieve a specific amount of work at a given

286    intensity such as maximum number of repetitions at 50% of one repetition maximum or at a

287    specific submaximal load[80-82] with less emphasis placed on the physiological adaptation required

288    for WC development. The American College of Sports Medicine (ACSM) have also defined strength

289    endurance, as 'high intensity' endurance.  As a result, strength endurance can be used as a proxy

290    measure of work capacity or as a  training variable within work capacity[70].

291

292    Failure to meet mechanical loading demands through insufficient neuromuscular capacity may

293    result in loss of optimal motor control and biomechanical inefficiency[83].  Trunk WC is underpinned

294    by the ability to transfer, absorb or dissipate, repeated or sustained submaximal forces through

295    appropriate strength endurance; providing a platform for the development and performance of

296    specific strength qualities.

297

298    Reduction in trunk muscle endurance and changes in endurance ratios have been identified in

299    patients with a history of LBP[84-86]; and insufficient abdominal muscular endurance has been

300    identified as a risk factor in injury recurrence[87].  Furthermore, structural degeneration of lumbar

301    musculature in LBP patients has been characterised by fatty infiltration, muscular atrophy and

302    fiber-type modification[88,89].  Static stabilisation ('pillar') exercises are frequently prescribed in an

303    attempt to produce sufficient muscular activation to develop spinal endurance qualities during

304    rehabilitation[12].  Targeted exercise has been shown to improve muscular strength[90], endurance[91]

305    and cross sectional area[92].

306

307    *Strength*

308

309    Muscular strength can be defined as the ability to produce force, with maximal strength being the

310    largest force the musculature can produce[93].  Rate of force development (RFD) has been defined

311    as the rate of rise of contractile force at the beginning of a muscle action and is time dependent[94].

312    RFD from trunk musculature can either augment global external power production (dynamic RFD)

313    or protect the spine by 'stiffening' against yielding forces (static RFD).  The production of

13

314    force/torque and stiffness depends on morphological and neurological factors from the

315    neuromuscular system.  Morphological factors include cross-sectional area, muscle pennation

316    angle, fascial length and fibre type[95].  Neurological factors include motor unit recruitment, firing

317    frequency, motor unit synchronisation and inter-muscular coordination[96].

318

319    *Dynamic RFD / power* - there is a growing body of evidence showing that athletes who produce

320    the greatest external powers are the most successful in their events[97,98]. Peak RFD has a strong

321    relationship with peak power and has been used as a proxy measure of peak power[93].  Watkins et

322    al. (1996)[99] suggest the trunk musculature assists in stabilising and controlling the load response

323    for maximal power during movements such as the golf swing.  During a single movement, maximal

324    power is the greatest instantaneous power with the aim of producing maximal velocity of

325    movements such as striking, kicking, jumping or throwing[100].  All of these tasks require segmental

326    sequential coordination to augment external global power output.

327

328    *Static RFD / stiffness* - could be defined as the ability of the trunk to resist deformation from

329    yielding forces to maintain spinal posture[101,102].  Muscular trunk stiffness requires contractile

330    forces equal to the rate, direction and magnitude exerted against the trunk to minimise the

331    transmission of force to the spine itself.  Similar morphological and neurological qualities are

332    required for appropriate stiffness capabilities as for power production[96,103,104]. The demand of the

333    task can require the trunk to brace against a rapid RFD under relatively low loads, biasing

334    challenge towards the neurological system[105].  By contrast, a high-imparted force also challenges

335    the neurological system but requires the morphological qualities of the trunk musculature to

336    produce stiffness large enough to protect the stability of the spine[95,106].

337

338    The association between trunk strength and the presence of LBP remains unclear, with evidence

339    to support[107-110] and contest[111,112] the relationship.  Despite the suggestion that trunk endurance

340    provides greater prophylactic value[113], strength and power is an essential physical requirement for

341    performance in many sports and represents the final stages of exercise progression for athletes

342    during rehabilitation from LSI[15].  In addition, failure to redevelop sufficient trunk strength during

343    the rehabilitation process may compromise the ability to maintain spinal integrity on return to

344    sporting activity and increase the risk of injury reoccurrence.

345

346

347    Figure 3: Classification of modifiable spinal abilities positioned within the context of physical

348    ability.

349

350

351    **Objective 2: Classification of spinal exercises according to objective of the exercise and intended**

352    **physical outcomes**

353

354    The classification of exercises is informed through empirical literature (e.g. motor control, work

355    capacity and strength) alongside the application of research within clinical practice (e.g. mobility

356    development).   Exercises were classified according to the objective of the exercise and the

357    intended physical outcome. In addition, exercises were also sub-classified by functionality, as

358    either  non-functional  (NF)  or  functional  (F);  and  by  spinal  displacement  as  either  static

359    (maintenance of a neutral spinal posture with no appreciable segmental displacement) or dynamic

360    (exercises involving appreciable dynamic segmental movement).

361

362    *Sub-classification 1: Functionality*

15

363

364     Functional exercises have been described as a continuum of exercises to enable athletes to

365     effectively manipulate their bodyweight in all planes of movement to achieve optimal athletic

366     performance[17]. Functional exercises are performed in weight bearing (standing, single leg

367     standing, squatting, lunging) or sport specific positions (multiple planes of motion involving

368     multiple joints). By contrast, non-functional exercises are typically performed in partial weight

369     bearing positions (sitting, kneeling, prone kneeling, lying) across a single plane of motion with

370     movement isolated to fewer joints[114]. An advantage of non-functional spinal exercises is the

371     ability to influence mechanical loading within specifically targeted muscle groups through use of

372     gravitational force, lever length (by manipulating body position), and superimposed load[115]. Both

373     non-functional and functional spinal exercise prescription can be utilised to develop effective

374     interaction (dynamic correspondence[116]) between physical abilities into sport specific

375     performance.

376

377     *Sub-classification 2: Spinal displacement*

378

379     During athletic activity, spinal function provides a static platform for force

380     absorption/transference or a dynamic contribution to whole body motion. The requirement for

381     these abilities is dependent on the movement demands of the sport which frequently requires

382     both components. During activities exposed to high loading characteristics, the central nervous

383     system employs stiffening strategies by co-contraction of antagonist trunk muscles with little or no

384     appreciable segmental displacement. In contrast, during tasks requiring appreciable dynamic

385     segmental movement, the central nervous system controls segmental motion through precision of

386     timing and pattern of muscle activity[14]. The ability to dissociate spinal and appendicular motion,

387    and perform sequential segmental spinal movement represents two discrete skill based

388    movement competencies.

389

390

391    **Spinal Exercise Classification (SEC)**

392

393    The definitive SEC is summarised in Figure 4.  Definitions of each exercise objective and examples

394    of exercises related to each intended physical outcome are displayed in Table 2 and Figures 5-11.

395    Exercises can be further delineated by plane of motion and/or globally targeted muscular

396    contraction[115]  (e.g. sagittal plane movement, anterior chain muscular activation).

397

398

399    Figure 4.  Spinal Exercise Classification (SEC) with exercise objectives positioned within context of

400    intended physical outcome

401

402

403    **Table 2. Exercise objective definitions positioned within context of intended physical outcome**

404

405

406    Figure 5. Mobility development - example exercises (a – flexion, b – extension, c – lateral flexion, d

407    – rotation)

408

409

410    Figure 6. Motor Control - example exercises, a) segmental stabilisation (non-functional) b) spinal

411    dissociation (non-functional), c) spinal dissociation (functional), d) segmental movement control

412    (non-functional), e) whole body co-ordination (functional)

413

414

415    Figure 7. Work Capacity - example exercises, a) pillar conditioning (non-functional), b) pillar

416    conditioning (functional)

417

418

419    Figure 8. Work Capacity - example exercises, a) segmental conditioning (non-functional), b)

420    segmental conditioning (functional)

421

422

423    Figure 9. Strength - example exercises, pillar strength development (non-functional)

424

425

426    Figure 10. Strength - example exercises, static rate of force / stiffness development (functional).

427    Note exercise selection biased towards morphological adaptation (a) and neurological adaptation

428    (b)

429

430    Figure 11. Strength - example exercises, dynamic rate of force / power development (functional)

431

432

433

434

**DISCUSSION**

Historically, there has been confusion regarding CS, how it is trained and its application to functional performance[9]. In addition, the most effective exercises for the treatment of LBP remain largely unknown and research evidence is unable to direct specific exercise prescription for a given pathological subgroup. During recent years, research has highlighted the complex interaction between anatomical, neurophysiological and psychosocial factors influencing spinal control. Failure to synthesise contemporary evidence can lead to reductionist opinion and uni-dimensional paradigms of exercise prescription; when in reality, the spine functions across a vast spectrum of movement demands, demonstrating complex interactions between many different modifiable physical abilities.

A qualitative consensus methodology was employed to systematically define the classification system to ensure acceptability to elite sport practitioners. The 4 phases worked well to ensure challenge to identified themes and sub themes with conclusions drawn from those experienced in sport at the elite level. The definitive SEC consolidates approaches to spinal exercise to develop a practical, conceptual representation of rehabilitation options applicable within a diverse spectrum of musculoskeletal practice. Furthermore, the classification supports multidisciplinary team integration within the rehabilitation process; demonstrating validity for use by strength and conditioning professionals as the athlete transitions towards performance focussed training following injury.

The intention of the SEC is to encourage detailed clinical reasoning, where practitioners identify specific physical dysfunction(s) and consider exercise prescription within the context of a clinical diagnosis and/or prevailing circumstances (e.g. sport specific performance targets). Once

19

460   determined, targeted exercise objectives define the nature of the exercise prescription required to

461   deliver an intended physical outcome.  In order for practitioners to effectively use the SEC, spinal

462   abilities need to be identified using outcome measures with established measurement properties.

463   Moreover, athletes are frequently able to compensate for sub-optimal abilities in various aspects

464   of physical performance.  Where the process of athlete evaluation identifies multidimensional

465   physical dysfunction, restoration of mobility and fundamental motor control must precede the

466   development of work capacity and strength.

467

468   It is intended that the SEC provides a platform for further research.  Future studies are required to

469   establish patterns of physical dysfunction within specific pathological subgroups; evaluate the

470   efficacy of exercise prescription in the development of specific physical performance abilities; and

471   evaluate the effect of targeted exercise within sporting populations with pathology.  The ability to

472   exhibit a wide breadth of physical abilities enhances performance and supports the capacity to

473   adapt to the variable nature of stress during sporting activity; contributing to the foundation of

474   injury prevention[117].

475

476   The strengths of this study are its attempt to define a common language, integration of a breadth

477   of literature and the intent to comprehensively evolve and incorporate (rather than replace or

478   discredit) existing theoretical frameworks extrapolated from a rapidly expanding knowledge base.

479   The key limitation to this study is the predominantly national focus to the consensus process,

480   although international experts were included at key stages.

481

482

483

484

485 **CONCLUSION**

486

487 Maintenance of spinal integrity during skilled athletic performance requires precise

488 neuromuscular control in order to balance task demands for stability and motion.   Economy of

489 motion is a function of discrete, interdependent physical abilities.  When investigating intrinsic

490 contribution to spinal injury, reductionist approaches may fail to accurately identify factors

491 associated with causality and predisposition.  Furthermore, comprehensive restoration of physical

492 abilities during rehabilitation is fundamental in the attainment of athletic performance and

493 mitigation of injury risk on return to sporting activity.  Exercise specificity forms the basis of

494 targeted adaptation, where intended physical outcome must dictate the nature of exercise

495 prescription.  The SEC contextualises spinal function and provides a basis for clinical reasoning and

496 targeted exercise selection in the prevention and management of spinal injuries in sport.

497

498

499 **Conflicts of Interest and Source of Funding**

500

501 There were no conflicts of interest.

502 There were no sources of funding.

503

504

505

506

507

508

509

510  **REFERENCES**

511

512  1.  Tall RL, DeVault W. Spinal injury in sport: epidemiologic considerations. *Clin Sports Med*.

513      1993;12(3):441-448.

514  2.  Bono CM. Low-back pain in athletes. *The Journal of bone and joint surgery American*

515      *volume*. 2004;86-A(2):382-396.

516  3.  Trainor TJ, Trainor MA. Etiology of low back pain in athletes. *Current sports medicine*

517      *reports*. 2004;3(1):41-46.

518  4.  d'Hemecourt PA, Gerbino PG, Micheli LJ. Back injuries in the young athlete. *Clin Sports*

519      *Med*. 2000;19(4):663-679.

520  5.  Ben Kibler W, Press J, Sciascia A. The role of core stability in athletic function. *Sports*

521      *medicine*. 2006;36(3):189-198.

522  6.  Cook G. Baseline Sports-Fitness Testing. In: *High-Performance Sports Conditioning*.

523      2001:19-47.

524  7.  Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. *Current*

525      *sports medicine reports*. 2008;7(1):39-44.

526  8.  Hodges P. Transversus abdominis: a different view of the elephant. *British journal of*

527      *sports medicine*. 2008;42(12):941-944.

528  9.  Faries M, Greenwood M. Core Training: stabilizing the confusion. *Strength and*

529      *Conditioning Journal*. 2007;29(2):10-25.

530  10.  Hodges PW. Core stability exercise in chronic low back pain. *The Orthopedic clinics of*

531     *North America*. 2003;34(2):245-254.

532     11.     Vleeming A, Vert Mooney MD, Stoeckart R. *Movement, Stability and Lumbopelvic Pain*.

533             Churchill Livingstone; 2007:489-561.

534     12.     Kavcic N, Grenier S, McGill SM. Determining the stabilizing role of individual torso

535             muscles during rehabilitation exercises. *Spine*. 2004;29(11):1254-1265.

536     13.     Cook G. *Athletic Body in Balance*. Stackpole Books; 2003:26-30.

537     14.     Hodges P, Cholewicki J. Functional control of the spine. In: *Movement, Stability and*

538             *Lumbopelvic Pain*. Churchill Livingstone; 2007:489-512.

539     15.     McGill S. *Ultimate Back Fitness and Performance*. 2006:277-285.

540     16.     Hodges PW, Gurfinkel VS, Brumagne S, Smith TC, Cordo PC. Coexistence of stability and

541             mobility in postural control: evidence from postural compensation for respiration. *Exp*

542             *Brain Res*. 2002;144(3):293-302.

543     17.     Boyle M. *Advances in Functional Training*. On Target Publications; 2012:31-34.

544     18.     Pepin JK, Preston D. Effects of Hold-Relax and Active Range of Motion on Thoracic Spine

545             Mobility. *J Int Acad Phys Ther Res*. 2012.

546     19.     Marshall RN, Elliott BC. Long-axis rotation: the missing link in proximal-to-distal

547             segmental sequencing. *J Sports Sci*. 2000;18(4):247-254.

548     20.     Young JL, Herring SA, Press JM, Casazza BA. The influence of the spine on the shoulder in

549             the throwing athlete. *J Back Musculoskelet Rehabil*. 1996;7(1):5-17.

550     21.     Vad VB, Bhat AL, Basrai D, Gebeh A, Aspergren DD, Andrews JR. Low back pain in

551    professional golfers: the role of associated hip and low back range-of-motion deficits. *Am*

552    *J Sports Med*. 2004;32(2):494-497.

553  22.  Campbell A, O'Sullivan P, Straker L, Elliott B, Reid M. Back pain in tennis players: a link

554    with lumbar serve kinematics and range of motion. *Med Sci Sports Exerc*. 2014;46(2):351-

555    357.

556  23.  Lindsay D, Horton J. Comparison of spine motion in elite golfers with and without low

557    back pain. *J Sports Sci*. 2002;20(8):599-605.

558  24.  Langevin HM, Sherman KJ. Pathophysiological model for chronic low back pain integrating

559    connective tissue and nervous system mechanisms. *Medical hypotheses*. 2007;68(1):74-

560    80.

561  25.  Sahrmann S. *Diagnosis and Treatment of Movement Impairment Syndromes*. Elsevier

562    Health Sciences; 2002:12-13.

563  26.  Cook G. *Movement*. Lotus Pub.; 2011:26-28.

564  27.  Simmonds N, Miller P, Gemmell H. A theoretical framework for the role of fascia in

565    manual therapy. *Journal of bodywork and movement therapies*. 2012;16(1):83-93.

566  28.  Schleip R, Müller DG. Training principles for fascial connective tissues: scientific

567    foundation and suggested practical applications. *J Bodyw Mov Ther*. 2013;17(1):103-115.

568  29.  Anderson VB. The intra-rater reliability of measured thoracic spine mobility in chronic

569    rotator cuff pathology. *J Musculoskelet Neuronal Interact*. 2011;11(4):314-319.

570  30.  Heneghan NR, Hall A, Hollands M, Balanos GM. Stability and intra-tester reliability of an in

571    vivo measurement of thoracic axial rotation using an innovative methodology. *Man Ther*.

572        2009;14(4):452-455.

573    31.    Johnson KD, Kim K-M, Yu B-K, Saliba SA, Grindstaff TL. Reliability of thoracic spine rotation

574        range-of-motion measurements in healthy adults. *J Athl Train*. 2012;47(1):52-60.

575    32.    Kellis E, Adamou G, Tzilios G, Emmanouilidou M. Reliability of spinal range of motion in

576        healthy boys using a skin-surface device. *J Manipulative Physiol Ther*. 2008;31(8):570-576.

577    33.    Battaglia G, Bellafiore M, Caramazza G, Paoli A, Bianco A, Palma A. Changes in spinal

578        range of motion after a flexibility training program in elderly women. *Clin Interv Aging*.

579        2014;9:653-660.

580    34.    Kuukkanen T, Mälkiä E. Effects of a three-month therapeutic exercise programme on

581        flexibility in subjects with low back pain. *Physiother Res Int*. 2000;5(1):46-61.

582    35.    Hodges PW, Moseley GL. Pain and motor control of the lumbopelvic region: effect and

583        possible mechanisms. *Journal of electromyography and kinesiology*. 2003;13(4):361-370.

584    36.    van Dieën JH, de Looze MP. Directionality of anticipatory activation of trunk muscles in a

585        lifting task depends on load knowledge. *Exp Brain Res*. 1999;128(3):397-404.

586    37.    Diedrichsen J, Shadmehr R, Ivry RB. The coordination of movement: optimal feedback

587        control and beyond. *Trends in cognitive sciences*. 2010;14(1):31-39.

588    38.    Silfies SP, Squillante D, Maurer P, Westcott S, Karduna AR. Trunk muscle recruitment

589        patterns in specific chronic low back pain populations. *Clin Biomech*. 2005;20(5):465-473.

590    39.    van Dieën JH, Selen LPJ, Cholewicki J. Trunk muscle activation in low-back pain patients,

591        an analysis of the literature. *J Electromyogr Kinesiol*. 2003;13(4):333-351.

592    40.    van Dieën JH, Cholewicki J, Radebold A. Trunk muscle recruitment patterns in patients

593           with low back pain enhance the stability of the lumbar spine. *Spine*. 2003;28(8):834-841.

594    41.    O'Sullivan P. Diagnosis and classification of chronic low back pain disorders: maladaptive

595           movement and motor control impairments as underlying mechanism. *Man Ther*.

596           2005;10(4):242-255.

597    42.    Van Dillen LR, Sahrmann SA, Norton BJ, Caldwell CA, Fleming DA, McDonnell MK, Woolsey

598           NB. Reliability of physical examination items used for classification of patients with low

599           back pain. *Phys Ther*. 1998;78(9):979-988.

600    43.    Hides JA, Boughen CL, Stanton WR, Strudwick MW, Wilson SJ. A magnetic resonance

601           imaging investigation of the transversus abdominis muscle during drawing-in of the

602           abdominal wall in elite Australian Football League players with and without low back

603           pain. *J Orthop Sports Phys Ther*. 2010;40(1):4-10.

604    44.    Cowan SM, Schache AG, Brukner P, Bennell KL, Hodges PW, Coburn P, Crossley KM.

605           Delayed onset of transversus abdominus in long-standing groin pain. *Med Sci Sports

606           Exerc*. 2004;36(12):2040-2045.

607    45.    Cholewicki J, Greene HS, Polzhofer GK, Galloway MT, Shah RA, Radebold A.

608           Neuromuscular function in athletes following recovery from a recent acute low back

609           injury. *J Orthop Sports Phys Ther*. 2002;32(11):568-575.

610    46.    D'hooge R, Hodges P, Tsao H, Hall L, Macdonald D, Danneels L. Altered trunk muscle

611           coordination during rapid trunk flexion in people in remission of recurrent low back pain.

612           *J Electromyogr Kinesiol*. 2013;23(1):173-181.

613    47.    Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K, Goldberg B. Delayed trunk

614          muscle reflex responses increase the risk of low back injuries. *Spine*. 2005;30(23):2614-

615          2620.

616    48.    Richardson CA, Jull GA. Muscle control-pain control. What exercises would you prescribe?

617          *Man Ther*. 1995;1(1):2-10.

618    49.    Tsao H, Hodges PW. Immediate changes in feedforward postural adjustments following

619          voluntary motor training. *Exp Brain Res*. 2007;181(4):537-546.

620    50.    Tsao H, Druitt TR, Schollum TM, Hodges PW. Motor training of the lumbar paraspinal

621          muscles induces immediate changes in motor coordination in patients with recurrent low

622          back pain. *J Pain*. 2010;11(11):1120-1128.

623    51.    Tsao H, Hodges PW. Persistence of improvements in postural strategies following motor

624          control training in people with recurrent low back pain. *J Electromyogr Kinesiol*.

625          2008;18(4):559-567.

626    52.    Gubler D, Mannion AF, Schenk P, Gorelick M, Helbling D, Gerber H, Toma V, Sprott H.

627          Ultrasound tissue Doppler imaging reveals no delay in abdominal muscle feed-forward

628          activity during rapid arm movements in patients with chronic low back pain. *Spine*.

629          2010;35(16):1506-1513.

630    53.    Vasseljen O, Unsgaard-Tøndel M, Westad C, Mork PJ. Effect of core stability exercises on

631          feed-forward activation of deep abdominal muscles in chronic low back pain: a

632          randomized controlled trial. *Spine*. 2012;37(13):1101-1108.

633    54.    Smith BE, Littlewood C, May S. An update of stabilisation exercises for low back pain: a

634          systematic review with meta-analysis. *BMC Musculoskelet Disord*. 2014;15(1):416.

635    55.    Adams MA, Dolan P. How to use the spine, pelvis, and legs effectively in lifting. In:

636           *Movement, Stability and Lumbopelvic Pain*. Churchill Livingstone; 2007:167-183.

637    56.    Cholewicki J, McGill SM. Lumbar posterior ligament involvement during extremely heavy

638           lifts estimated from fluoroscopic measurements. *J Biomech*. 1992;25(1):17-28.

639    57.    Monnier A, Heuer J, Norman K, Äng BO. Inter- and intra-observer reliability of clinical

640           movement-control tests for marines. *BMC Musculoskelet Disord*. 2012;13(1):263.

641    58.    Luomajoki H, Kool J, de Bruin ED, Airaksinen O. Movement control tests of the low back;

642           evaluation of the difference between patients with low back pain and healthy controls.

643           *BMC Musculoskelet Disord*. 2008;9:170.

644    59.    Hodges PW. Pain and motor control: From the laboratory to rehabilitation. *Journal of*

645           *electromyography and kinesiology*. 2011;21(2):220-228.

646    60.    Panjabi MM. Clinical spinal instability and low back pain. *Journal of electromyography and*

647           *kinesiology.* 2003;13(4):371-379.

648    61.    Harris-Hayes M, Van Dillen LR, Sahrmann SA. Classification, treatment and outcomes of a

649           patient with lumbar extension syndrome. *Physiother Theory Pract*. 2005;21(3):181-196.

650    62.    Elqueta-Cancino E, Schabrun S, Danneels L, Hodges P. A clinical test of lumbopelvic

651           control: Development and reliability of a clinical test of dissociation of lumbopelvic and

652           thoracolumbar motion. *Man Ther*. 2014;19(5):418-24.

653    63.    Brumagne S, Lysens R, Spaepen A. Lumbosacral position sense during pelvic tilting in men

654           and women without low back pain: test development and reliability assessment. *J Orthop*

655           *Sports Phys Ther*. 1999;29(6):345-351.

656    64.    Higgins S. Motor skill acquisition. *Phys Ther*. 1991;71(2):123-139.

657    65.    Schmidt RA. *Motor Learning and Performance*. Human Kinetics; 2008:379-384.

658    66.    Guadagnoli MA, Lee TD. Challenge point: a framework for conceptualizing the effects of

659           various practice conditions in motor learning. *Journal of motor behavior*. 2004;36(2):212-

660           224.

661    67.    Ranganathan R, Newell KM. Changing up the routine: intervention-induced variability in

662           motor learning. *Exercise and sport sciences reviews*. 2013;41(1):64-70.

663    68.    Ericsson K, Krampe R, Tesch-Römer C. The role of deliberate practice in the acquisition of

664           expert performance. *Psychological review*. 1993;100(3):363-406.

665    69.    Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: a review

666           and critical reappraisal. *Psychol Bull*. 1984;95(3):355-386.

667    70.    Ratamess NA, Alvar A, Evetoch TK, Housh TJ, Kibler WB, Kraemer WJ, Triplett NT.

668           American College of Sports Medicine position stand. Progression models in resistance

669           training for healthy adults. *Med Sci Sports Exerc*. 2009;41(3):687-708.

670    71.    Siff MC. *Supertraining*. Supertraining Institute; 2003:32-33.

671    72.    Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour

672           contribute to the increase in contraction speed after dynamic training in humans. *The*

673           *Journal of Physiology*. 1998;513(1):295-305.

674    73.    Connor MK, Bezborodova O, Escobar CP, Hood DA. Effect of contractile activity on protein

675           turnover in skeletal muscle mitochondrial subfractions. *J Appl Physiol*. 2000;88(5):1601-

676           1606.

677    74.    Frontera WR, Hughes VA, Fielding RA, Fiatarone MA, Evans WJ, Roubenoff R. Aging of

678          skeletal muscle: a 12-yr longitudinal study. *J Appl Physiol*. 2000;88(4):1321-1326.

679    75.    Langberg H, Skovgaard D, Asp S, Kjaer M. Time pattern of exercise-induced changes in

680          type I collagen turnover after prolonged endurance exercise in humans. *Calcif Tissue Int*.

681          2000;67(1):41-44.

682    76.    Miller BF, Olesen JL, Hansen M, Dossing S, Crameri RM, Welling RJ, Langberg H, Flyvberg

683          A, Kjaer M, Babraj JA, Smith K, Rennie MJ. Coordinated collagen and muscle protein

684          synthesis in human patella tendon and quadriceps muscle after exercise. *The Journal of*

685          *Physiology*. 2005;567(Pt 3):1021-1033.

686    77.    Kongsgaard M, Reitelseder S, Pedersen TG, Holm L, Aagaard P, Kjaer M, Magnusson SP.

687          Region specific patellar tendon hypertrophy in humans following resistance training. *Acta*

688          *Physiol*. 2007;191(2):111-121.

689    78.    Burd NA, West DWD, Staples AW, Atherton PJ, Baker JM, Moore DR, Holwerda AM, Parise

690          G, Rennie MJ, Baker SK, Phillips SM. Low-load high volume resistance exercise stimulates

691          muscle protein synthesis more than high-load low volume resistance exercise in young

692          men. *PLoS ONE*. 2010;5(8):e12033.

693    79.    Gonzalez Castro LN, Monsen CB, Smith MA. The binding of learning to action in motor

694          adaptation. *PLoS Comput Biol*. 2011;7(6):e1002052.

695    80.    Liu Y, Lormes W, Wang L, Reissnecker S, Steinacker JM. Different skeletal muscle HSP70

696          responses to high-intensity strength training and low-intensity endurance training. *Eur J*

697          *Appl Physiol*. 2004;91(2-3):330-335.

698    81.    Naclerio FJ, Colado JC, Rhea MR, Bunker D, Triplett NT. The influence of strength and

699   power on muscle endurance test performance. *J Strength Cond Res*. 2009;23(5):1482-

700   1488.

701 82. Jürimäe T, Perez-Turpin JA, Cortell-Tormo JM, Chinchilla-Mira IJ, Cejuela-Anta R, Maestu J,

702   Purge P, Jürimäe J . Relationship between rowing ergometer performance and

703   physiological responses to upper and lower body exercises in rowers. *J Sci Med Sport*.

704   2010;13(4):434-437.

705 83. Borghuis J, Hof AL, Lemmink KAPM. The importance of sensory-motor control in providing

706   core stability: implications for measurement and training. *Sports medicine*.

707   2008;38(11):893-916.

708 84. Salminen JJ, Maki P, Oksanen A, Pentti J. Spinal mobility and trunk muscle strength in 15-

709   year-old schoolchildren with and without low-back pain. *Spine*. 1992;17(4):405-411.

710 85. Bo Andersen L, Wedderkopp N, Leboeuf-Yde C. Association between back pain and

711   physical fitness in adolescents. *Spine*. 2006;31(15):1740-1744.

712 86. McGill S, Grenier S, Bluhm M, Preuss R, Brown S, Russell C. Previous history of LBP with

713   work loss is related to lingering deficits in biomechanical, physiological, personal,

714   psychosocial and motor control characteristics. *Ergonomics*. 2003;46(7):731-746.

715 87. Jones MA, Stratton G, Reilly T, Unnithan VB. Biological risk indicators for recurrent non-

716   specific low back pain in adolescents. 2005;39(3):137-140.

717 88. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper HJ. CT imaging of

718   trunk muscles in chronic low back pain patients and healthy control subjects. *Eur Spine J*.

719   2000;9(4):266-272.

720    89.    D'hooge R, Cagnie B, Crombez G, Vanderstraeten G, Dolphens M, Danneels L. Increased

721           intramuscular fatty infiltration without differences in lumbar muscle cross-sectional area

722           during remission of unilateral recurrent low back pain. *Man Ther*. 2012;17(6):584-588.

723    90.    Keller A, Brox JI, Gunderson R, Holm I, Friis A, Reikerås O. Trunk muscle strength, cross-

724           sectional area, and density in patients with chronic low back pain randomized to lumbar

725           fusion or cognitive intervention and exercises. *Spine*. 2004;29(1):3-8.

726    91.    Durall CJ, Udermann BE, Johansen DR, Gibson B, Reineke DM, Reuteman P. The effects of

727           preseason trunk muscle training on low-back pain occurrence in women collegiate

728           gymnasts. *J Strength Cond Res*. 2009;23(1):86-92.

729    92.    Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, Bourgois J, Dankaerts W, De

730           Cuyper HJ. Effects of three different training modalities on the cross sectional area of the

731           lumbar multifidus muscle in patients with chronic low back pain. 2001;35(3):186-191.

732    93.    Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL, Hartman

733           M. The importance of isometric maximum strength and peak rate-of-force development

734           in sprint cycling. *J Strength Cond Res*. 2004;18(4):878-884.

735    94.    Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of

736           force development and neural drive of human skeletal muscle following resistance

737           training. *J Appl Physiol*. 2002;93(4):1318-1326.

738    95.    Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: Part 1--

739           biological basis of maximal power production. *Sports Med*. 2011;41(1):17-38.

740    96.    Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve

741           analysis of the countermovement jump: impact of training. *J Strength Cond Res*.

742       2009;23(1):177-186.

743    97.    Stone MH, Sanborn K, O'Bryant HS, Hartman M, Stone ME, Proulx C, Ward B, Hruby J.

744        Maximum strength-power-performance relationships in collegiate throwers. *J Strength*

745        *Cond Res*. 2003;17(4):739-745.

746    98.    Nimphius S, McGuigan MR, Newton RU. Relationship between strength, power, speed,

747        and change of direction performance of female softball players. *J Strength Cond Res*.

748        2010;24(4):885-895.

749    99.    Watkins RG, Uppal GS, Perry J, Pink M, Dinsay JM. Dynamic electromyographic analysis of

750        trunk musculature in professional golfers. *Am J Sports Med*. 1996;24(4):535-538.

751    100.    Newton RU, Kraemer WJ. Developing Explosive Muscular Power: Implications for a Mixed

752        Methods Training Strategy. J Strength Cond. 1994;16:20-31.

753    101.    Graham RB, Brown SHM. A direct comparison of spine rotational stiffness and dynamic

754        spine stability during repetitive lifting tasks. *J Biomech*. 2012;45(9):1593-1600.

755    102.    Brown SHM, McGill SM. How the inherent stiffness of the in vivo human trunk varies with

756        changing magnitudes of muscular activation. *Clin Biomech*. 2008;23(1):15-22.

757    103.    Brughelli M, Cronin J. A review of research on the mechanical stiffness in running and

758        jumping: methodology and implications. 2008;18(4):417-426.

759    104.    Chelly SM, Denis C. Leg power and hopping stiffness: relationship with sprint running

760        performance. *Med Sci Sports Exerc*. 2001;33(2):326-333.

761    105.    Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: part 2 -

762        training considerations for improving maximal power production. *Sports Med*.

763        2011;41(2):125-146.

764   106.    Brown SHM, McGill SM. Muscle force-stiffness characteristics influence joint stability: a

765        spine example. *Clin Biomech*. 2005;20(9):917-922.

766   107.    Bayramoğlu M, Akman MN, Kilinç S, Cetin N, Yavuz N, Ozker R. Isokinetic measurement of

767        trunk muscle strength in women with chronic low-back pain. *Am J Phys Med Rehabil*.

768        2001;80(9):650-655.

769   108.    McNeill T, Warwick D, Andersson G, Schultz A. Trunk strengths in attempted flexion,

770        extension, and lateral bending in healthy subjects and patients with low-back disorders.

771        *Spine*. 1980;5(6):529-538.

772   109.    Davarian S, Maroufi N, Ebrahimi I, Farahmand F, Parnianpour M. Trunk muscles strength

773        and endurance in chronic low back pain patients with and without clinical instability. *J

774        Back Musculoskelet Rehabil*. 2012;25(2):123-129.

775   110.    McGill SM, Grenier S, Kavcic N, Cholewicki J. Coordination of muscle activity to assure

776        stability of the lumbar spine. *Journal of electromyography and kinesiology*.

777        2003;13(4):353-359.

778   111.    Paalanne N, Korpelainen R, Taimela S, Remes J, Mutanen P, Karppinen J. Isometric trunk

779        muscle strength and body sway in relation to low back pain in young adults. *Spine*.

780        2008;33(13):E435-E441.

781   112.    Renkawitz T, Boluki D, Grifka J. The association of low back pain, neuromuscular

782        imbalance, and trunk extension strength in athletes. *Spine J*. 2006;6(6):673-683.

783   113.    McGill SM. Low back exercises: evidence for improving exercise regimens. *Phys Ther*.

784        1998;78(7):754-765.

785    114.    Gambetta V. *Athletic Development*. New World Library; 2007:3-4.

786    115.    Floyd RT, Thompson C. Basic Biomechanical Factors and Concepts. In: *Manual of*

787        *Structural Kinesiology*. McGraw-Hill; 2009:69-86.

788    116.    Siff MC. Dynamic Correspondence as a Means of Strength Training. In: *Supertraining*.

789        Supertraining Institute; 2003:240-252.

790    117.    Glasgow P, Bleakley CM, Phillips N. Being able to adapt to variable stimuli: the key driver

791        in injury and illness prevention? *British journal of sports medicine*. 2013;47(2):64-65.

792