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Lumbopelvic muscle activation patterns in adolescent fast bowlers

Mitchell Forrest¹, Mark Hecimovich² & Alasdair Dempsey¹

¹School of Psychology and Exercise Science, Murdoch University, Murdoch, WA 6150, Australia,

²Division of Athletic Training, School of Health, Physical Education and Leisure Studies, College of Education, University of Northern Iowa, Cedar Falls, IA, USA

Abstract

Introduction: Adolescent fast bowlers are prone to sustaining lumbar injuries. Numerous components have been identified as contributing factors; however, there is limited empirical evidence outlining how the muscles of the lumbopelvic region, which play a vital role in stabilising the spine, function during the bowling action and the influence of such activation on injuries in the fast bowler. *Methods:* Surface electromyography was utilised to measure the function of the lumbar erector spinae, lumbar multifidus, gluteus medius and gluteus maximus muscles bilaterally during the fast bowling action in a group of 35 cricket fast bowlers aged 12–16 years. *Results:* Two prominent periods of activation occurred in each of the muscles examined. The period of greatest mean activation in the erector spinae and multifidus occurred near back foot contact (BFC) and within the post-ball-release (BR) phase. The period of greatest mean activation for the gluteus medius and gluteus maximus occurred during phases of ipsilateral foot contact. *Discussion:* The greatest periods of muscle activation in the paraspinal and gluteal muscles occurred at times where vertical forces were high such as BFC, and in the phases near BR where substantial shear forces are present. *Conclusion:* The posterior muscles within the lumbopelvic region appear to play a prominent role during the bowling action, specifically when compressive and shear forces are high. Further research is required to substantiate these findings and establish the role of the lumbopelvic muscles in the aetiology of lumbar injury in the cricket fast bowler.

Keywords: Cricket, lumbopelvic, bowler, stability, electromyography, activation

Introduction

Fast bowlers miss more playing time through injury than any other type of cricketer, most often with injuries to the trunk and lower back (Orchard, James, Alcott, Carter, & Farhart, 2002). Soft tissue injuries such as those to the muscles, tendons or ligaments are common amongst fast bowling populations, particularly injuries of this nature to abdominal and lumbar regions (Orchard, James, Portus, Kountouris, & Dennis, 2009). Abnormalities in the lumbar region such as pars interarticularis defects, stress fractures and intervertebral disc degeneration are also common in the adolescent fast bowler with rates of 33–54% (Crewe, Elliott, Couanis, Campbell, & Alderson, 2012; Hardcastle et al., 1992) and 58–63% (Burnett et al., 1996; Hardcastle et al., 1992) respectively, for lumbar vertebral and intervertebral disc abnormalities.

The aetiology of lower back injury in the cricket fast bowler is multi-factorial with age, mechanical factors, bowling technique and poor lumbopelvic-hip stability playing a role (Bayne, Elliott, Campbell, & Alderson, 2016; Elliott, 2000). In regard to age, high rates of lumbar abnormalities are observed in adolescent fast bowlers (Burnett et al., 1996; Crewe et al., 2012; Hardcastle et al., 1992), as bony ossification may not take place until 20–30 years of age, and the intervertebral disc is still highly elastic (Cyron & Hutton, 1978). Various mechanical factors such as large compressive and shear loads brought about by substantial ground reaction forces (Bartlett, Stockill, Elliott, & Burnett, 1996) and rapid, asymmetrical, trunk movements (Crewe, Campbell, Elliott, & Alderson, 2013) also influence injury (Elliott, 2000). In combination, these compressive and shear loads increase the stress on the intervertebral disc (Schmidt et al., 2007), and bony components such as the pars interarticularis (Chosa, Totoribe, & Tajima, 2004), two common sites of injury in the fast bowler (Hardcastle et al., 1992). Bowling technique, specifically excessive trunk movements in the transverse (Burnett et al., 1996; Foster, John, Elliott, Ackland, & Fitch, 1989; Hardcastle et al., 1992) and frontal planes (Bayne et al., 2016; Ranson, Burnett, King, Patel, & O'Sullivan, 2008) also influence lumbar injury in the fast bowler. For example, excessive shoulder counter rotation (SCR) has been linked with abnormalities in the lumbar vertebra and intervertebral disk (Burnett et al., 1996; Foster et al., 1989; Hardcastle et al., 1992), with excessive lateral trunk flexion to the side

contralateral to the bowling arm linked with soft tissue and bony lumbar injuries (Bayne et al., 2016; Ranson et al., 2008). Although the exact mechanism linking SCR to lumbar injury, has yet to be definitively established (Crewe et al., 2013; Ranson et al., 2008), excessive lateral trunk flexion to the side contralateral to the bowling arm is suggested to influence injury as it often takes place near the end range of motion (ROM) (Ranson et al., 2008) where tissue damage is more likely to take place (McGill, 1997). The majority of bony abnormalities in the lumbar spine of the fast bowler also occur on the side contralateral to the bowling arm and thus further support the suggestion that excessive lateral trunk flexion to this side influences lumbar injury (Debnath et al., 2007; Hardcastle et al., 1992). Fast bowlers with reduced control of the lumbopelvic region are more likely to present with radiographically identified bony lumbar abnormalities and lumbar injuries (Bayne et al., 2016). In addition, fast bowlers with poor pelvi-femoral control or inadequate single leg balance are more susceptible to sustaining injuries in the lumbar region/lower limb and exhibit excessive degrees of lateral trunk flexion and pelvic rotation during the bowling action (Bayne et al., 2016; Olivier, Stewart, Olorunju, & McKinnon, 2015).

Various muscles in the lumbopelvic-hip region such as the paraspinal and gluteal muscles play a vital role in stabilising the region (Gottschalk, Kourosh, & Leveau, 1989; Powers, 2010; Vleeming, Pool-Goudzwaard, Stoeckart, van Wingerden, & Snijders, 1995; Wilke, Wolf, Claes, Arand, & Wiesend, 1995) and when acting antagonistically, limit excessive trunk movements (Saunders, Schache, Rath, & Hodges, 2005; Thorstensson, Carlson, Zomlefer, & Nilsson, 1982). As an inability to control the lumbopelvic-hip region may predispose a fast bowler to injury (Bayne et al., 2016; Olivier et al., 2015), by allowing excessive trunk movements during the bowling action (Bayne et al., 2016; Burnett et al., 1996; Foster et al., 1989; Hardcastle et al., 1992; Ranson et al., 2008), it is likely that the role of the paraspinal and gluteal muscles is imperative during the bowling action.

No published study has directly assessed the function of the paraspinal and gluteal muscles in the fast bowler during the bowling action. This study therefore employed surface electromyography (sEMG) to assess the activation patterns of the lumbar erector spinae (ES), lumbar multifidus (MF), gluteus maximus (GMX) and the gluteus medius (GMD) during the bowling action in a group of adolescent

fast bowlers. This novel investigation provides important information as to the *in situ* function of the posterior lumbopelvic muscles and outlines their potential role in both the development of injury and injury prevention techniques in the fast bowler.

Methods

Participants

Thirty-five male, medium/fast bowlers between the ages of 12–16 (mean age: 13.9 ± 1.2 years; mean height: 173 ± 11.7 cm; mean weight 60 ± 14.1 kg) were recruited for this study. All bowlers were enrolled in an under 12–16 cricket team competing at various levels in an Australian metropolitan area and were required to have played at least one full season of cricket prior to their participation in the study. Exclusion criteria included any current injury which prevented the bowler from performing as they would in a match situation, congenital lumbar deformities, and, previous lumbar spine surgery.

Experimental overview

All procedures were carried out at the Human Performance Lab at Murdoch University. Participants and their parent/guardian were required to sign a written consent form in accordance with the policy of Human Research Ethics Committee at Murdoch University (2014/221) to volunteer to participate in the study. Prior to participation, subjects completed a health history and demographic questionnaire (age, weight, height, previous and current injury status, history of cricket-related low back pain, dominant bowling side) and underwent a warm-up procedure that included 5 min of moderate aerobic exercise and a general stretching programme of the upper and lower extremities. One practise delivery was then given to allow the participant to mark out their run-up and familiarise themselves with the laboratory environment. Participants were then prepared for sEMG and electrodes were placed on four lumbopelvic muscles bilaterally. Baseline muscle tests were performed on all muscles to obtain a maximal voluntary contraction (MVC). Participants were then asked to complete a bowling task,

consisting of four medium/fast deliveries, during which the muscle activation of the four examined muscles was assessed with sEMG.

Electromyography

The electrical activity of the ES, MF, GMD and GMX was measured bilaterally with sEMG [Noraxon, Direct Transmission System (DTS)] during the bowling action. Disposable Ag/AgCl surface electrodes (Duo-Trode) with an inter-electrode spacing of 21 ± 1 mm were placed bilaterally on all examined muscles as per previously utilised locations (Hermens et al., 1999; Leinonen, Kankaanpaa, Airaksinen, & Hanninen, 2000; Semciw, Green, Pizzari, & Briggs, 2013). The underside of each DTS sensor was secured to the skin with double sided adhesive tape and further secured with a film of dressing tape to reduce signal artefacts. Following electrode placement, participants were asked to perform one MVC for each of the examined muscles. For the ES and MF MVC, the participant lay prone and was instructed to extend the trunk while resisting load applied by the examiner in the direction of trunk flexion. For the GMX MVC, the participant lay prone while extending the leg at the hip with a flexed knee. The examiner then applied a load in the direction of hip flexion which the participant was required to resist. For the GMD MVC, the participant lay prone with the leg abducted at the hip (midpoint of abduction ROM) and in slight hip external rotation. The examiner then applied a load in the direction of hip adduction which the participant was required to resist. All MVCs took place over a 4-s period during which the participant was instructed to contract maximally and hold against the resistance.

Bowling task

During the bowling task participants bowled four deliveries which were required to hit a target on the bounce. The target was placed directly behind the wickets at the batting end to simulate an appropriate bowling zone for a right-handed batsman. Deliveries which missed the target were re-bowled. Bowlers were instructed to bowl off their full run-up and perform as they would in a match situation. A 1-min rest was given between deliveries and a further 5-min rest given if six balls were bowled before four successful deliveries were performed. The electrical activity of the examined muscles was

recorded over a 2-s period with a remote trigger used to begin the recording process. The examiner operating the trigger ensured 100 ms prior to back foot contact (BFC) and 100 ms post-ball-release (BR) were captured within the 2-s period. The bowling action in the sagittal and transverse plane was recorded in 2D at 200 fps using Qualisys Track Manager software. The video data were synchronised with the sEMG data to ensure bowling time points such as BFC, front foot contact (FFC) and BR could be identified within the sEMG data. Data to obtain SCR during the bowling action were also collected as per Portus, Mason, Elliott, Pfitzner, and Done (2004).

Data analysis

Raw EMG data were processed using custom MATLAB scripts. Data were then band-pass filtered with a high pass cut-off of 30 Hz and a low pass cut-off of 500 Hz using a fourth order Butterworth filter. Data were then wave rectified and low pass filtered at 6 Hz using a fourth order Butterworth filter to create linear envelopes. To establish within-subject sEMG values, the mean muscular activity from four bowling trials was used. The magnitude of activation was reported as a percentage of each participant's MVC or if greater, a percentage of the maximal peak in activation during the bowling action for each muscle. To account for differences in the duration of the bowling action between subjects, all trials were normalised as a percentage, with 100 ms prior to BFC and 100 ms post-BR corresponding to 0–100% respectively. The timing of BFC, FFC and BR was determined subjectively upon review of the recorded video data as per Portus, Rosemond, and Rath (2006) and Worthington, King, and Ranson (2013). The data from all left-handed bowlers were normalised to that of the right-handed bowlers. Four phases were identified within the bowling action: preparation (100 ms prior to BFC–BFC); stride (BFC–FFC); delivery (FFC–BR) and recovery (BR–100 ms post-BR).

Statistical analysis

To investigate whether differences existed between individual muscle activation between phases, a three-way, repeated-measures analysis of variance was conducted, with the factors of muscle, side and phase. A Pearson's correlation coefficient was used to assess the relationship between SCR and

individual mean muscle activity between BFC and FFC (stride phase). Statistical significance was set at $p < .05$ and the results expressed as mean \pm SD.

Results

When examining the timing of bowling events amongst all bowlers mean BFC occurred at 21%, mean FFC at 57% and mean BR at 81% of the bowling action. Each muscle displayed two prominent peaks in activation throughout the bowling action (refer to Figure 1). The first peak in activity took place after BFC with the exception of the left GMD which peaked slightly prior. The second peak in the gluteal muscles took place just prior to BR with the paraspinal muscles peaking slightly after BR.

Comparisons between the muscle activity of the left and right sided muscles between phases is displayed in (Figure 2). The greatest magnitude of activation in the right ES (54% MVC \pm 15, $p < .001$) and both right MF (58% MVC \pm 18, $p = .001$) and left MF (55% MVC \pm 15, $p = .036$) occurred within the recovery phase, however, the left ES experienced its highest period of activation within the stride phase (54% MVC \pm 11, $p = .007$). The greatest period of activation in the right-sided gluteal muscles occurred within the stride phase (GMD 44% MVC \pm 15, $p = .037$; GMX 51% MVC \pm 14, $p < .001$) with the greatest period of activation in the left-sided gluteal muscles occurring within the delivery phase (GMD 52% MVC \pm 18; GMX 56% MVC \pm 15). This activation in the left-sided gluteal muscles, however, did not differ significantly to the levels of muscle activation occurring in the recovery phase ($p > .05$)

The mean SCR in this study was $36.7^\circ \pm 11.3$. When comparing the subject's SCR to their mean muscle activity between BFC and FFC (stride phase), no statistically significant results were demonstrated (Table I).

Discussion

In the current study, the ES and MF activated prominently during the stride phase where significant ground reaction forces associated with BFC impact the body (Bartlett et al., 1996) and during the delivery and recovery phases where large degrees of trunk flexion and lateral trunk flexion away from the bowling arm are documented (Burnett, Barrett, Marshall, Elliott, & Day, 1998; Ranson et al., 2008). Comparisons can be made between the patterns of ES and MF activation during the bowling action and the patterns observed during walking and running, where these muscles activate to limit lateral trunk flexion contralateral to the stance side and trunk flexion (Saunders et al., 2005; Thorstensson et al., 1982). The ES and MF are also documented to act in the same manner during standing trunk flexion and lateral trunk flexion to the contralateral side (Kuriyama & Ito, 2005; Leinonen et al., 2000). Excessive lateral flexion between FFC and BR is suggested to influence spinal injury (Ranson et al., 2008), with fast bowlers exhibiting greater lateral flexion at BR (50° compared to 40°) being more prone to lumbar injury and radiographically identified bony lumbar abnormalities (Bayne et al., 2016). The antagonistic function of the ES and MF during the delivery and recovery phases, especially the muscles ipsilateral to the bowling arm, are of particular interest as they may serve to limit excessive trunk movement during the bowling action (Saunders et al., 2005; Thorstensson et al., 1982). The MF also contributes greatly to spinal stability (Wilke et al., 1995) and may therefore act to protect the spine from the substantial compressive (Bartlett et al., 1996) and shear forces (Crewe et al., 2013) impacting on it throughout the bowling action.

During the bowling action, gluteal muscle activation was most prominent during periods of ipsilateral foot contact, where large ground reaction forces are present (Bartlett et al., 1996). The GMD is suggested to activate at this time to stabilise the pelvis in the frontal plane (Gottschalk et al., 1989; Powers, 2010), and to provide force closure to the hip joint (Gottschalk et al., 1989). Activation of the GMX at this time is likely occurring to propel the body forwards, prevent the hip and trunk from buckling into flexion (Lieberman, Raichlen, Pontzer, Bramble, & Cutright-Smith, 2006), to assist in transferring force from the lower limb via the thoracolumbar fascia to the spine and to provide force closure to the sacroiliac joint (Vleeming et al., 1995; van Wingerden, Vleeming, Buyruk, & Raissadat,

2004). As a result, the gluteal muscles may act as preliminary force mediators, negotiating load as it transfers through the hip joint, sacroiliac joint and the thoracolumbar fascia before impacting the spine. Deficiencies in the function of the gluteal muscles could potentially produce pathomechanical loading patterns (Plummer & Oliver, 2013) which may inappropriately load the lumbopelvic region and result in injury.

Inadequate lumbopelvic stability, reduced pelvi-femoral control and poor single leg balance are characteristics of fast bowlers who are prone to sustaining injuries, and who exhibit greater degrees of lateral trunk flexion and pelvic rotation during the bowling action, which likely exposes them to greater loads (Bayne et al., 2016; Olivier et al., 2015). As the paraspinal and gluteal muscles are ideally suited to stabilising the lumbopelvic-hip region (Gottschalk et al., 1989; Powers, 2010; Vleeming et al., 1995; Wilke et al., 1995), their function during the bowling action, specifically at times where large compressive forces are present such as BFC and FFC (Bartlett et al., 1996), is suggested to be vital.

The link between excessive SCR and lumbar injury in the fast bowler has been established, however, the exact mechanism remains elusive (Burnett et al., 1996; Foster et al., 1989; Hardcastle et al., 1992). This study aimed to assess if a link could be established between the degree of SCR and the mean magnitude of muscle activity within the stride phase. The stride phase was chosen as the point of analysis as it is where the majority of SCR occurs. The results revealed that no relationship existed between the degree of SCR and the mean magnitude of muscle activity for any of the examined muscles in this study. It is likely that the activation patterns of the muscles were influenced by a range of factors, namely trunk movements in the sagittal and frontal plane, and thus a distinction could not be made between a bowler's SCR and the degree of muscle activity occurring in relation to this transvers plane kinematic. It is possible however, that the activation patterns of the internal and external oblique muscles would more closely relate to the degree of SCR exhibited by a bowler, as these muscles primarily drive trunk rotation. A relatively large variation in the degree of SCR ($36.7^\circ \pm 11.3$) was also observed between subjects in this study. If the variation within this specific

phase of the bowling action was generalised to the remaining phases of the bowling action, it could explain the large standard deviations presented within the data of Figures 1 and 2.

Several limitations have been identified in the current study. For example, only four posterior lumbopelvic muscles were investigated bilaterally. To better understand the function of the lumbopelvic region during the bowling action the abdominal muscles and the deeper posterior lumbopelvic muscles such as the quadratus lumborum would also need to be investigated. Various limitations are also associated with the use of sEMG such as signal cross talk and signal stability, two factors that may have influenced the results of this study (De Luca, 1997). In addition, kinematical information was only collected during the stride phase and thus, only speculation can be made as to the influence of a particular muscle's activation on movement or stability throughout the bowling action. Finally, some error may have occurred when establishing the timing of events such as BFC, FFC and BR as this determination was made subjectively.

Conclusion

The results from this study outline the *in situ* function of the posterior lumbopelvic muscles during the bowling action and provide insight into their potential influence on both injury and injury prevention mechanism in the fast bowler. Paraspinal muscle activation was at its greatest when the trunk was moving through dynamic ranges such as flexion and lateral flexion, suggesting these muscles play an important role in eccentrically controlling the trunk. Gluteal muscle activation primarily occurred during ipsilateral foot contact where large ground reaction forces transition up through the body. The gluteal muscles may therefore play an important role in mediating forces before they reach the spine and controlling the pelvi-femoral region, a factor previously linked with the development of lumbar injury in the fast bowler. Further research is needed to substantiate these findings and should aim to establish if a link can be made between muscle activation patterns and certain kinematical features observed through the bowling action. Specifically, kinematic features which have previously been linked to lumbar injury in the cricket fast bowler.

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References

- Bartlett, R., Stockill, N., Elliott, B., & Burnett, A. (1996). The biomechanics of fast bowling in men's cricket: A review. *Journal of Sports Sciences*, *14*(5), 403–424.
- Bayne, H., Elliott, B., Campbell, A., & Alderson, J. (2016). Lumbar load in adolescent fast bowlers: A prospective injury study. *Journal of Science and Medicine in Sport*, *19*(2), 117–122.
- Burnett, A., Barrett, C. J., Marshall, R. N., Elliott, B. C., & Day, R. E. (1998). Three-dimensional measurement of lumbar spine kinematics for fast bowlers in cricket. *Clinical Biomechanics*, *13*(8), 574–583.
- Burnett, A., Khangure, M., Elliott, B., Foster, D., Marshall, R., & Hardcastle, P. (1996). Thoracolumbar disc degeneration in young fast bowlers in cricket: A follow-up study. *Clinical Biomechanics*, *11*(6), 305–310.
- Chosa, E., Totoribe, K., & Tajima, N. (2004). A biomechanical study of lumbar spondylolysis based on a three-dimensional finite element method. *Journal of Orthopaedic Research*, *22*(1), 158–163
- Crewe, H., Campbell, A., Elliott, B., & Alderson, J. (2013). Lumbo-pelvic loading during fast bowling in adolescent cricketers: The influence of bowling speed and technique. *Journal of Sports Sciences*, *31*(10), 1082–1090.
- Crewe, H., Elliott, B., Couanis, G., Campbell, A., & Alderson, J. (2012). The lumbar spine of the young cricket fast bowler: An MRI study. *Journal of Science and Medicine in Sport*, *15*(3), 190–194.
- Cyron, B., & Hutton, W. (1978). The fatigue strength of the lumbar neural arch in spondylolysis. *Journal of Bone & Joint Surgery: British Volume*, *60*(2), 234–238
- Debnath, U. K., Freeman, B. J. C., Grevitt, M. P., Sithole, J., Scammell, B. E., & Webb, J. K. (2007). Clinical outcome of symptomatic unilateral stress injuries of the lumbar pars interarticularis. *Spine*, *32*(9), 995–1000.
- De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, *13*, 135–163.
- Elliott, B. C. (2000). Back injuries and the fast bowler in cricket. *Journal of Sports Sciences*, *18*(12), 983–991.
- Foster, D., John, D., Elliott, B., Ackland, T., & Fitch, K. (1989). Back injuries to fast bowlers in cricket: A prospective study. *British Journal of Sports Medicine*, *23*(3), 150–154.
- Gottschalk, F., Kourosch, S., & Leveau, B. (1989). The functional anatomy of tensor fasciae latae and gluteus medius and minimus. *Journal of Anatomy*, *166*, 179–189
- Hardcastle, P., Annear, P., Foster, D. H., Chakera, T. M., McCormick, C., Khangure, M., & Burnett, A. (1992). Spinal abnormalities in young fast bowlers. *Journal of Bone and Joint Surgery*, *74*(3), 421–425

- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., ... Hägg, G. (1999). European recommendations for surface electromyography. *Roessingh Research and Development, Enschede*, 8(2), 13–54
- Kuriyama, N., & Ito, H. (2005). Electromyographic functional analysis of the lumbar spinal muscles with low back pain. *Journal of Nippon Medical School*, 72(3), 165–173.
- Leinonen, V., Kankaanpää, M., Airaksinen, O., & Hanninen, O. (2000). Back and hip extensor activities during trunk flexion/extension: Effects of low back pain and rehabilitation. *Archives of Physical Medicine and Rehabilitation*, 81(1), 32–37.
- Lieberman, D. E., Raichlen, D. A., Pontzer, H., Bramble, D. M., & Cutright-Smith, E. (2006). The human gluteus maximus and its role in running. *Journal of Experimental Biology*, 209(11), 2143–2155.
- McGill, S. M. (1997). The biomechanics of low back injury: Implications on current practice in industry and the clinic. *Journal of Biomechanics*, 30(5), 465–475
- Olivier, B., Stewart, A., Olorunju, S., & McKinnon, W. (2015). Static and dynamic balance ability, lumbo-pelvic movement control and injury incidence in cricket pace bowlers. *Journal of Science and Medicine in Sport*, 18(1), 19–25
- Orchard, J., James, T., Alcott, E., Carter, S., & Farhart, P. (2002). Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine*, 36(4), 270–274
- Orchard, J., James, T., Portus, M., Kountouris, A., & Dennis, R. (2009). Fast bowlers in cricket demonstrate up to 3-to 4-week delay between high workloads and increased risk of injury. *The American Journal of Sports Medicine*, 37(6), 1186–1192
- Plummer, H. A., & Oliver, G. D. (2013). The relationship between gluteal muscle activation and throwing kinematics in baseball and softball catchers. *Journal of Strength and Conditioning Research*, 28(1), 87–96
- Portus, M., Mason, B. R., Elliott, B. C., Pfitzner, M. C., & Done, R. P. (2004). Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sports Biomechanics* 3(2), 263–284.
- Portus, M., Rosemond, C. D., & Rath, D. A. (2006). Cricket: Fast bowling arm actions and the illegal delivery law in men's high performance cricket matches. *Sports Biomechanics*, 5(2), 215–230.
- Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), 42–51
- Ranson, C. A., Burnett, A. F., King, M., Patel, N., & O'Sullivan, P. B. (2008). The relationship between bowling action classification and three-dimensional lower trunk motion in fast bowlers in cricket. *Journal of Sports Sciences*, 26(3), 267–276
- Saunders, S. W., Schache, A., Rath, D., & Hodges, P. W. (2005). Changes in three dimensional lumbo-pelvic kinematics and trunk muscle activity with speed and mode of locomotion. *Clinical Biomechanics*, 20(8), 784–793
- Schmidt, H., Kettler, A., Heuer, F., Simon, U., Claes, L., & Wilke, H.-J. (2007). Intradiscal pressure, shear strain, and fiber strain in the intervertebral disc under combined loading. *Spine*, 32(7), 748–755
- Semciw, A. I., Green, R. A., Pizzari, T., & Briggs, C. (2013). Verification of a standardized method for inserting intramuscular EMG electrodes into uniquely oriented segments of gluteus minimus and gluteus medius. *Clinical Anatomy*, 26(2), 244–252
- Thorstensson, A., Carlson, H., Zomlefer, M. R., & Nilsson, J. (1982). Lumbar back muscle activity in relation to trunk movements during locomotion in man. *Acta Physiologica Scandinavica*, 116(1), 13–20.

- Vleeming, A., Pool-Goudzwaard, A. L., Stoeckart, R., van Wingerden, J.-P., & Snijders, C. J. (1995). The posterior layer of the thoracolumbar fascia its function in load transfer from Spine to Legs. *Spine*, 20(7), 753–758
- van Wingerden, J.-P., Vleeming, A., Buyruk, H., & Raissadat, K. (2004). Stabilization of the sacroiliac joint in vivo: Verification of muscular contribution to force closure of the pelvis. *European Spine Journal*, 13(3), 199–205.
- Wilke, H. -J., Wolf, S., Claes, L. E., Arand, M., & Wiesend, A. (1995). Stability increase of the lumbar spine with different muscle groups: A biomechanical in vitro study. *Spine*, 20(2), 192–197.
- Worthington, P. J., King, M. A., & Ranson, C. A. (2013). Relationships between fast bowling technique and ball release speed in cricket. *Journal of Applied Biomechanics*, 29(1), 78–84.

Figure 1. Mean magnitude of muscle activation throughout the bowling action. *Note:* Mean activation (solid line) and \pm SD (broken lines). BFC, FFC and BR are marked at 21, 57 and 81%, respectively. 100% MVC = 1.

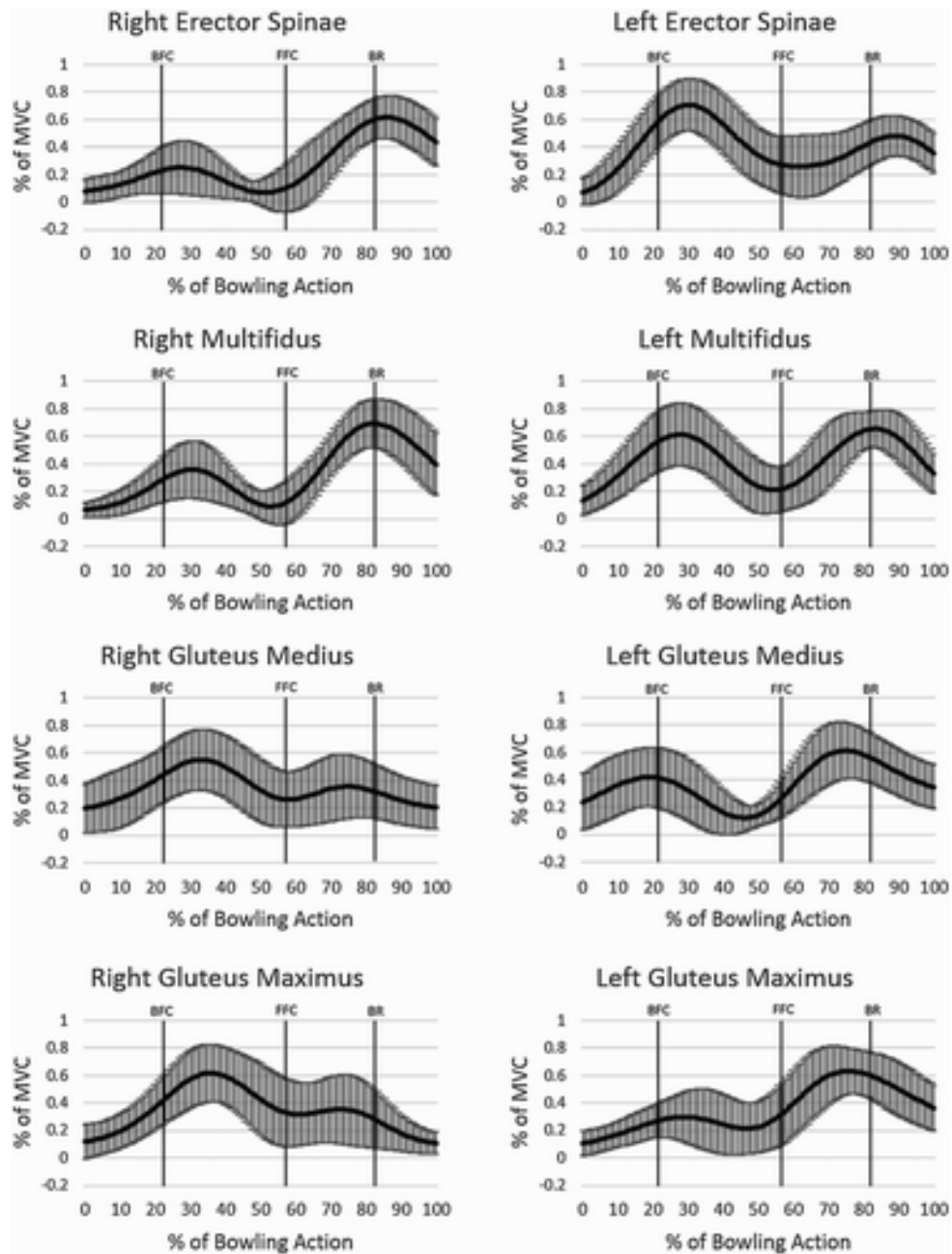


Figure 2. Mean magnitude of muscle activation within bowling phases. *Note:* Mean magnitude of activation and \pm SD (right- and left-sided comparisons). 100% of MVC = 1.

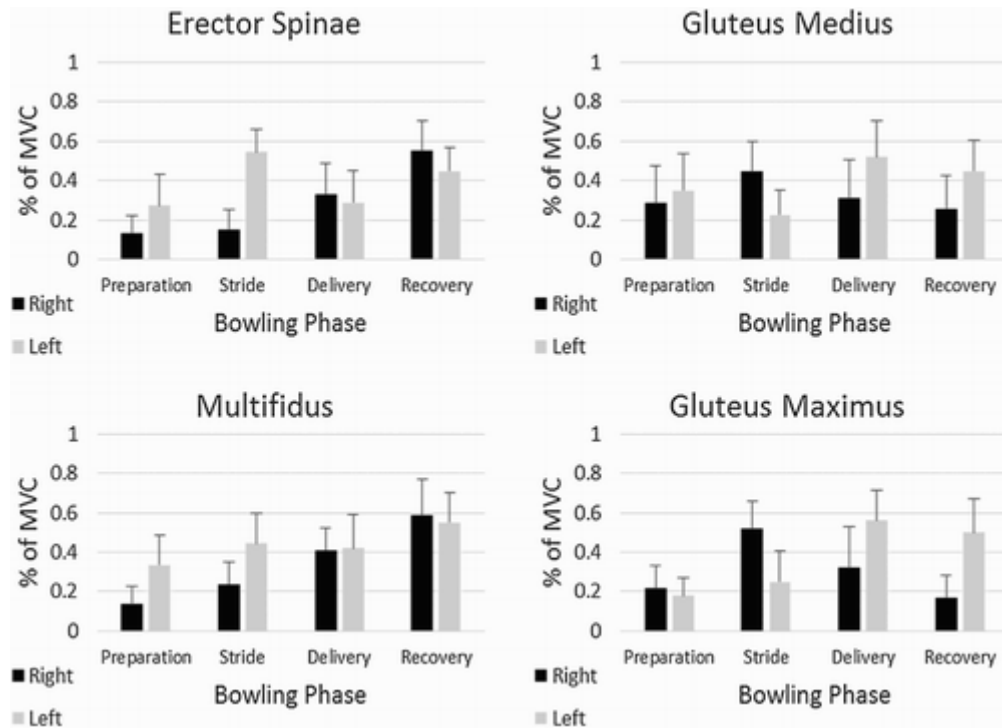


Table I. SCR and mean muscle activity within the stride phase.

| | Right ES | Left ES | Right MF | Left MF | Right GMD | Left GMD | Right GMX | Left GMX |
|--------------------|-----------------|----------------|-----------------|----------------|------------------|-----------------|------------------|-----------------|
| Pearson's <i>r</i> | -.132 | .109 | -.138 | -.195 | .141 | .264 | -.012 | .239 |