BRIDGING THE NEXUS BETWEEN SIMULATION & INJURY PREVENTION

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The goal of this communication is to show how human musculoskeletal modelling and simulation research can be used to help translate injury related research to effective real-world injury prevention practice. Specifically, we will show how relevant musculoskeletal and simulation research was used in the development of 1) reliable video based lower-limb injury screening tools and 2) a novel biomechanically informed lower-limb and ACL injury prevention training intervention. Special attention will be placed on how musculoskeletal and simulation research underpinned the development of the screening tools and injury prevention training protocol.

KEY WORDS: ACL, Knee, Lower-limb, Injury prevention, Rehabilitation

INTRODUCTION: Technological advancements such as the invention of stop-action photography (Muybridge E., 1878), the force platform (Elfman H., 1938) and the programmable computer have allowed the field of biomechanics to emerge as an important discipline within the life, physical and sport sciences. With parallel improvements in motion capture technologies, musculoskeletal modelling, and human simulation, we as sport scientists have the ability, more than any time in history the ability to measure forces at the joint and tissue level during the high velocity sporting tasks injuries are known to occur. The sport biomechanist has therefore emerged as a central figure for our understanding of the mechanical aetiology (external and internal forces) of musculoskeletal injury risk in sport.

The reason musculoskeletal injuries are of interest to the sport biomechanist is because they are a global health care problem, costing governments world-wide hundreds of billions of dollars annually (Donnelly et al, 2012a; Finch et al., 2015; Gianotti et al, 2009). One lower limb injury that stands out among all others are ruptures to the anterior cruciate ligament (ACL). The reason is because commonplace treatments for a ruptured ACL are surgical reconstructions (Strehl & Eggli., 2007), which are coupled with long rehabilitation periods (2-12 months)(Hartigan et al., 2010) and high rates of re-injury (Orchard et al., 2001).

Currently, there is research available showing that in principle, combinations of different training genres, such as balance, plyometric, resistance, and/or technique training can reduce lower limb and ACL injury risk/rates among adolescent female populations (< 18 yrs) (Donnelly et al., 2012a). However, there is comparably little evidence supporting this generalized training approach for reducing injury risk among adult and male team sport athletes (Andrew et al., 2013). One cannot overlook that fact that injury prevention is a complex, multifaceted problem. However, it can be argued that one contributing factor to these incomplete injury outcomes is because lower limb injury prevention training interventions have been developed and implemented without a clear mechanistic (e.g. biomechanical/neuromuscular) understanding of how the prescribed exercises within the intervention can reduce injury risk during the sporting tasks injuries are known to occur. As a result, there is a rationale for sport biomechanics researchers to consciously deliberate on how to maximise the training content within these interventions to more effectively translate lower limb and ACL injury prevention research among heterogeneous sporting populations world-wide.

The purpose of this communication will be to provide the reader with applied examples of how the biomechanist, when armed with relevant musculoskeletal and simulation research can assist in the development of 1) injury risk screening tools and 2) injury prevention training protocols. Special attention will be placed on the empirical rationale for the development of a novel Biomechanically-informed lower-limb and ACL injury prevention training protocols for use among team sport athletes.

RELEVENT MUSCULOSKELETAL & SIMULATION RESEARCH: Within the musculoskeletal modelling framework OpenSim (SimTK.org), the residual reduction algorithm can be used to optimizing an athlete's movement profile (i.e., technique) to reduce their injury risk in sport. Using this novel *in-silico* computational method, Donnelly et al. (2012c) proved a causal relationship exists between an athlete's upper body mechanics, knee loading and injury risk during unplanned sidestepping sporting tasks (Figure 1). The applied message from this research is that the dynamic control of the upper body during sporting tasks is of paramount importance for reducing an athlete's lower limb injury risk in sport.

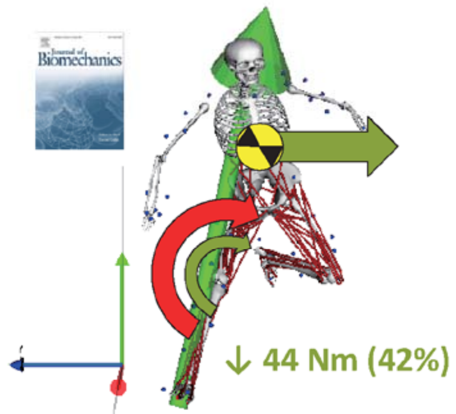

Figure 1: Dynamic control of the trunk segment is paramount for lower limb and ACL injury risk.

Again, within OpenSim, the computed muscle control computational framework can be used to calculate and characterize the muscle forces an athlete uses during dynamic sporting tasks. When simulating the single leg-landing muscle mechanics of Australian football players during the impact phase of landing, Morgan et al. (2014) showed that the gastrocnemius muscles are used significantly more than the hamstrings to stiffen and support the knee during the impact phase, which is where injury risk is thought to be the greatest (Donnelly et al. 2012a). These findings have challenged over 30 years of clinical research, which have presumed the hamstrings, with the quadriceps are responsible for supporting the knee during the impact phase of landing. The applied message from this research is that the gastrocnemius muscles play an important role in supporting the knee against externally applied knee loads during single-leg landing tasks.

Using vector field statistics, Robinson et al. (2015) proved an athlete's knee flexion angle at the impact phase of unanticipated stepping is correlated with non-sagittal plane knee moments, known risk factors associated with ACL injury risk. Though these results seem intuitive, a mechanical link between sagittal plane knee kinematics and the knee moments known to elevate ACL injury risk in sport had not yet been established. With the use of vector field statistics, recommending an athlete to increase their knee flexion angle at impact is a sound technique recommendation to reduce and athlete's injury risk in sport.

Lastly, '*dynamic valgus*' knee postures, or then '*inward buckling*' (medial frontal plane shift) of the knee is predictive of ACL injury among adolescent female populations (R^2 = 0.88) (Hewett et al., 2005). Though observed at the knee, the '*dynamic valgus*' posture is the result of excessive hip internal rotation and adduction, combined with knee flexion. Consequently, a '*dynamic valgus*' knee posture is likely attributed to poor hip neuromuscular control during dynamic sporting tasks.

APPLICATIONS TO INJURY SCREENING: From the aforementioned musculoskeletal and simulation based research, it is clear an athlete's upper body motor control and knee flexion dynamics influences their non-sagittal plane knee moments during sporting tasks. Using this research as a foundation, our group has developed a reliable (ICC = 0.65-0.96) 2D video based screening tool capable of predicting young (13-17yrs) female athlete's peak frontal (R=0.75; p = 0.001) and sagittal (R=0.70; p = 0.045) plane knee moments during unplanned sidestepping tasks from six upper and lower body kinematic variables (primarily trunk and knee flexion kinematics)(Weir et al., 2013)(Figure 2). From this pilot research, our group is currently collecting and processing data from elite female field hockey plays, junior male football players and elite male football players to determine if the aforementioned 2D lower limb injury risk

Figure 2: Overview of injury screening tool & exercise prescription platform. From left to right, i) video recording, ii) subject-specific risk assessment, iii) subject-specific exercise prescription.

screening tool is repeatable across different sporting codes, participation levels, age groups as well as between genders. If successful, we will have a robust and reliable 2D video based tool appropriate for the mass screening of athletes in field based settings. If used appropriately, sport scientists will have the ability to identify at-risk athletes for the prescription of personalized training programs to mitigate this risk (Fox et al., 2016).

APPLICATIONS TO INJURY PREVENTION TRAINING: From the aforementioned musculoskeletal and simulation based research highlighted above, our group has developed Biomechanically-informed injury prevention training program (i.e., content), with the delivery of which underpinned by behaviour change theory (Figure 3). Due to space, we will discuss the content of the Biomechanically-informed injury prevention training. This should not diminish the importance of behaviour change theory for the effective delivery of injury prevention training interventions. The reason is because many lower limb injury prevention studies have identified athlete compliance and adherence to the intervention as a major barrier to its success or lack thereof (Donnelly et al. 2012a, 2012b). For the effective real-world translation of injury prevention research (i.e., content), we must also incorporate established psychological principles (i.e., communication, training, instructional) in both its design and implementation if we are to engage program recipients and see the intended prophylactic effects of the intervention received by the participants.

The four pillars of Biomechanically-informed injury prevention training are to improve an athlete's: 1) knee flexion dynamics during impact, 2) dynamic trunk control, 3) gastrocnemius muscle strength and 4) hip external rotator strength during change of direction and landing tasks. Armed with this novel injury prevention training approach, which is focused explicitly on targeting the biomechanical mechanisms associated with injury risk rather than combinations of different training genres (e.g., plyometric, balance, resistance); we trialled this intervention among community and elite level athletes.

In collaboration with the Australian Women's Hockey team, we implemented biomechanically informed injury prevention training alongside their 2012-2013 training schedule, four sessions/week, 20 min/day. Immediate outcomes (i.e., following 9-weeks) from the intervention saw 'high-risk' athletes' reduce their peak valgus knee moments and subsequent injury risk predisposition by 28% (p = 0.003) (Weir et al., 2014a). Following prolonged exposure (i.e., following 25-weeks), the entire training group reduced their peak valgus knee

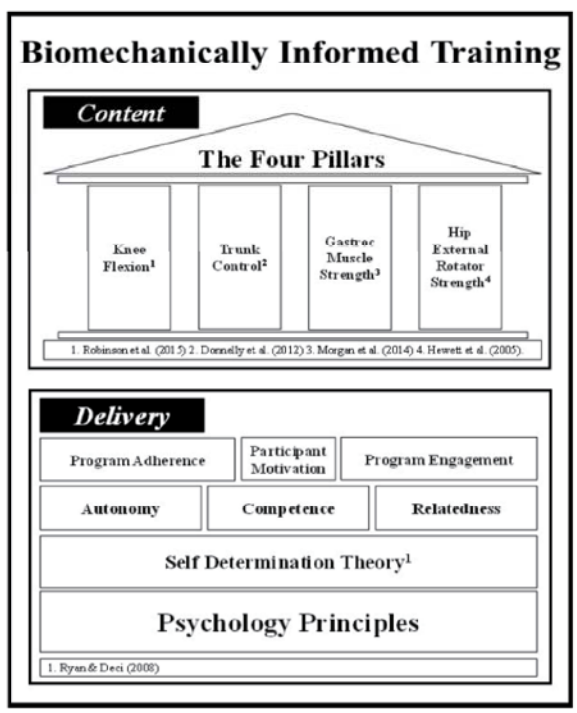

Figure 3: Overview of biomechanically informed training

moments and injury risk by 26% (g = 0.30)(Weir et al., 2015a). In addition, two years following the training intervention, there were no incidences of non-contact ACL injuries among athletes who participated in the trial, while total lower limb injury rates were reduced (Weir et al, 2015b). In addition to these positive injury outcomes, athletes also reported increases in their athletic performance, proving in principle that reductions in injury incidence and increases in athletic performance are not mutually exclusive outcomes from a training intervention.

Biomechanically-informed injury prevention training was also implemented as a clinical control trial among community-level female hockey players (two sessions/week, 15-20 min/day). Acute outcomes from the intervention (i.e., 9-weeks), showed the comparison group displayed moderate-to-large increases in both peak valgus (Δ+27%, d = -0.36) and internal rotation (Δ+38%, d = -0.56) knee moments, with negligible-to-no changes observed within the intervention group (Staynor et al., 2015). These training results show that even low volume Biomechanically-informed injury prevention training can be used to mitigate the potential deleterious effects of regular season community-based sport participation (Donnelly et al. 2012b).

This research have shown that Biomechanically-informed injury prevention training is effective in reducing an athlete's ACL injury risk and ACL/lower-limb injury rates in sport, while improving their sport performance. Therein, there is a rationale for clinicians and coaches to expand their philosophy of injury prevention training prescriptions; shifting their focus from the type of exercises within an injury prevention training intervention (e.g., combinations of plyometric, balance, resistance etc.), to the intended biomechanical focus of the exercises used within it. It is through this mechanistic approach the sport biomechanist can better assist in the effective translation of injury prevention research to injury prevention practice world-wide.

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REFERENCES:

Andrew N., Gabbe B., Cook J., Lloyd D., Donnelly C.J., Nash C. and Finch C.F. (2013) Could targeted exercise programs prevent lower limb injury in community Australian Football? Sports Medicine. 43:751-763.

Donnelly, C.J., Elliott, B.C., Ackland T.R., Doyle T.L.A, Besier T.F., Finch, C.F., Cochrane, J.L., Dempsey A.R. and Lloyd, D.G. (2012a). An anterior cruciate ligament injury prevention framework: Incorporating the recent evidence. Res Sports Med. 20(3-4):239-62.

Donnelly C.J., Elliott, B.C., Doyle, T.L.A., Finch, C.F., Dempsey, A.R. and Lloyd, D.G. (2012b). Changes in knee joint biomechanics following balance and technique training and a season of Australian football. Br J Sports Med. 46(13):917-22.

Donnelly, C.J., Elliott, B., Lloyd, D.G. and Reinbolt, J.A. (2012c). Optimizing Whole body Kinematics to minimize valgus knee loading during sidestepping: Implications for ACL injury risk. J Biomech. 45(8):1491-1497.

Elfman H. (1938). The measurement of the external forces in walking. *Science*, 88(2276):152-153.

Finch, C.F., Kemp, J.L., and Clapperton, A.J. (2015). The incidence and burden of hospital-treated sports-related injury in people aged 15+ years in Victoria, Australia, 2004-2010: A future epidemic of osteoarthritis? *Osteoarthritis Cartilage*. 23(7):1138-43.

Fox A.S., Bonacci J., McLean S.G., Spittle M., Saunders N. (2016). A Systematic Evaluation of Field-Based Screening Methods for the Assessment of Anterior Cruciate Ligament (ACL) Injury Risk. *Sports Med.* 46(5):715-35.

Gianotti, S.M., Marshall, S.W., Hume, P.A., and Blunt, L. 2009. Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. *J Sci Med Sport*. 12(6), 622-627.

Hartigan, E.H., Axe, M.J., and Snyder-Mackler, L. (2010). Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. *J Orth Sport PhysTher*. 40(3):141-54.
Hewett, T.E., Myer, G.D., Ford, K.R., Heidt, R.H., Colosimo, A.J., McLean, S.G., van den Bogert, A.J., Paterno, M.V., Succop, P. (2005). Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes. *Am J Sports Med*. 33(4):492-501.
Morgan, K, Donnelly, C.J. and Reinbolt, J.A (2014). Elevated Gastrocnemius Forces Compensate for Decreased Hamstrings Forces during the Weight-Acceptance Phase of Single-Leg Jump Landing: Implications for Anterior Cruciate Ligament Injury Risk. J Biomech. 47(13):3295-302.
Muybridge E. (1878). The Science of the horse's Motion. *Scientific America: October 19.*
Orchard, J., Seward, H., McGivern, J., and Hood, S. (2001). Intrinsic and extrinsic risk factors for anterior cruciate ligament injury in Australian footballers. *Am J Sports Med*. 29(2):196-200.
Robinson, M.A., Donnelly, C.J., Vanrenterghem, J., Pataky, T.C. Sagittal plane knee kinematics predict non-sagittal knee joint moments in unplanned sidestepping. In proceedings of the XXV Congress of the International Society of Biomechanics, Glasgow, Scotland, July 12-16, 2015.
Staynor, J.M.D., Nicholas, J.C., Weir, G., Alderson, J., and Donnelly, C.J. The effect of biomechanically focused injury prevention training on reducing anterior cruciate ligament injury risk among female community level athletes. In proceedings of the 33rd International Conference on Biomechanics in Sports, Poitiers, France, June 29 – July 3, 2015.
Strehl, A., and Eggli, S. (2007). The value of conservative treatment in ruptures of the anterior cruciate ligament (ACL). *J Trauma*. 62(5):1159-62.
Weir, G., Alderson, J., Elliott, B., Lee, S., and Donnelly, C.J. How much is enough? Maintaining the biomechanical benefits of an ACL injury prevention training program. In proceedings of the 33rd International Conference on Biomechanics in Sports, Poitiers, France, June 29 – July 3, 2015a.
Weir, G., Alderson, J., Elliott, B., Cooke, J., Starre, K., Jackson, B., Donnelly, C.J. Injury prevention and athletic performance are not mutually exclusive: An anterior cruciate ligament injury prevention training program. In proceedings of the annual Sport Medicine Australia conference, Sanctuary Cove, Queensland. October 21-24, 2015b.
Weir, G.J., Smailes, N., Alderson, J., Elliott, B.C., and Donnelly, C.J. A Two-Dimensional Video Based Screening Tool To Predict Peak Knee Loading and ACL Injury Risk in Female Community Level Athletes. In proceedings of the XXIV Congress of the International Society of Biomechanics, Natal, Brazil, August 4-9, 2013.