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The theme developed in this position paper follows the current evolution of injury prevention in the backs of workers. Job change or 'fitting the task to the person' has come far, but will probably not result in zero injury rates. This is because the cause of injury is heavily influenced by the way that a worker moves. A review of injury mechanisms reveals the need for the biomechanist/ergonomist to incorporate features in biomechanical models that recognise these injury mechanisms. The implication of one such model is that the next leap toward a zero injury rate may be approached with 'fitting the person to the task' or at least retraining the way that workers move. A few examples of movement-based back injury prevention strategies are provided. Finally, some thoughts on implementing such an approach are expressed. This is a review and position paper written in honour of Professor Don Chaffin's career.

Keywords: worker training; back injury; ergonomics; biomechanics

1. Introduction

The theme developed in this position paper follows the current evolution of injury prevention in the backs of workers. Job change or 'fitting the task to the person' has come far but will probably not result in zero injury rates. This is because the cause of injury is heavily influenced by the way that a worker moves (see the multi-perspective summaries in McGill 2007, Marras 2008). These movement-based variables include the muscle activation patterns that ultimately determine the stability of the spine and the load imposed on the spinal joints, together with subtle movements within the spine that influence tissue stresses and their breaking tolerance. One implication of this approach is that the next leap toward zero injury may be approached with reversing the axiom 'fitting the task to the person' to 'fit the person to the task'. More specifically, this means training the way that workers move. Evidence for this proposal is presented as a review of injury mechanisms together with a few examples of movement-based back injury prevention strategies. Finally, some thoughts on implementing such an approach are expressed.

The debate between psychosocial and biomechanical factors as a cause of back troubles has raged. While different opinions exist regarding the relative role and importance of these two factors, those studies that made reasonably robust measures of both psychosocial and biomechanical factors have shown that both are important but that mechanical loading, at least for low back injury, dominates (see, for example, Marras *et al.* 1995, Norman *et al.* 1998). However, joint loading is also a function of personal factors such as joint motion and the muscle activation patterns that individual workers choose to utilise. In addition, muscular co-contraction and hip stiffness, among others, are examples of factors that have been shown to affect joint load and future absenteeism due to back troubles (McGill *et al.* 2003). Interestingly, Marras *et al.* (2000) has shown that psychosocial profiles, specifically personality profiles, can influence muscular co-activation about a joint, demonstrating that psychological and biomechanical factors are not independent and distinct. Perhaps it is not surprising that ergonomics has not reduced injury rates to the levels hoped for, but, unfortunately, this is often erroneously used as evidence that the physical factors are unimportant. Ergonomists have also set the unrealistic goal of 'zero' injury rates. This is probably not achievable. Even with an 'ergonomically correct', or well-designed job, some will still experience pain or injury. This is because so much of the loading experienced by joints is generated not by external loads, but by the muscles themselves. People use different strategies to activate muscles and move through motion patterns even when performing identical jobs. Further, not only are muscles used to create force for movement, they also must be highly coordinated to ensure stability of the joints to prevent

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injurious buckling, for example. Thus, the way that people choose to move plays a large role in determining their risk of injury. While physical ergonomics is important, it is only a component in a broader effort needed to achieve minimal injury rates. 'Fitting the task to the person' has been the mantra of ergonomists. The position taken here is that one must return, at least partially, to consider 'fitting the person to the task' or, more precisely, training the way the individual moves. To create a basis for this argument, numerous injury mechanisms, based on individual factors, are listed and discussed.

2. Predicting risk: factors other than job design

The objective of early work was to develop an anatomically detailed, biomechanical model of the back driven by the biological signals obtained directly from each subject. In this way, as the individual moved and activated muscle, these movement and muscle activation patterns were used to drive the 3-D, anatomical model. (This was in contrast with the more popular approach of the day that used optimisation models, which did not account for individual strategies for muscle activation or movement patterns.) Passive tissue force-time histories were obtained from their stress–strain profiles. Muscle forces were obtained from electromyographic (EMG) signals and adjusted for the known modulators of force, such as velocity, length, size, etc. Total joint loads and reaction moments were then calculated. This approach led to the ability to assess the different ways that workers moved to accomplish similar jobs. Of course, many movement patterns are constrained by the design of the job. As has been pointed out by Professor Marras (Marras *et al.* 2001) and others, there simply is not a safe or justifiable way for workers to repeatedly pick heavy objects from the floor. So starting height is governed by job design. But if the weight is raised to the height such that a worker can move about the hips without flexing the spine, substantial loads can be lifted. In fact, lifting with no spine motion from low levels so that all of the flexion motion occurs at the hips is a marker for elite lifting performance and injury avoidance in the weightlifting world (McGill 2006). Obviously, fatigue will change patterns and may affect these mechanics compromising injury risk. Thus, endurance, or lack thereof, has been shown to be predictive of future back trouble episodes (and must be addressed appropriately). Specifically, Biering-Sorensen (1984) in his classic study on 449 men and 479 women documented how those with greater spine motion range and less extensor muscle endurance had an increased risk of first-time back injuries.

Other impediments exist to achieving a workforce with healthy backs. Common wisdoms such as stretching the back or enhancing the mobility of the spine are popular, yet appear to have no scientific foundation. Stretching deadens the neural response (Kokkonen *et al.* 1998, Solomonow *et al.* 2000) and replicates, among others, the injury mechanism for discogenic conditions (Callaghan and McGill 2001). Those with healthy backs tend to utilise very low spine power – in other words, if they have high spine loads they have virtually no spine motion (McGill 2006). Olympic lifters provide a wonderful example of maximising hip power and minimising spine power to lift without back troubles. They violate popular ergonomic guidelines for load limits, yet rarely experience back injury. Spine posture is another example of a variable that can result in a strengthening of the spine to bear load by up to 40% – yet this has little to do with 'trunk flexion' but rather 'spine posture' (Gunning *et al.* 2001). Specifically, maintaining the spine in a neutral posture ensures the most resilient spine possible – the implication being that bending is accomplished with the 'hip hinge'. The work on spine motion and flexibility has also shown that spine mobility has little to do with predicting who will get better following back injury (Parks *et al.* 2003).

Examples from the sporting world assist with understanding of cause and consequence of musculoskeletal injury. Cholewicki's group (Cholewicki *et al.* 2005) has shown that by following 292 athletes for 2–3 years, they were able to predict 74% of future back injuries by measuring the muscle reflex latencies in the muscles of the torso shutting off after a quick release paradigm. Thus, these perturbed responses were linked with a cause of future back troubles. Yet on the other hand, in a slightly smaller study group (n = 242), the same research group based at Yale (Reeves *et al.* 2006) found imbalances between the back thoracic and lumbar musculature in those with a history of back troubles, suggesting that these were a consequence of having back troubles and not predictive of suffering them in the future. There are better developed databases to illustrate this concept for other body joints. For example, in the knee injury literature, a study of 277 collegiate athletes (Zazulak *et al.* 2007a) showed that those with less control of the trunk after a quickly released load, poorer proprioception and who had a history of back pain predicted future knee injury. Specifically, prediction accuracy was 84%, 89% and 91% in females, for each of these variables, while only a history of back pain predicted knee injury in males. In a follow-up publication by Zazulak *et al.* (2007b), impaired proprioception was found to distinguish the females who sustained knee injury. Dynamic knee and hip stability mechanics were thought to be linked to spine and torso stability and thus attributed part of the pathway for female susceptibility. In a similar line of thought, Beckman and Buchanan (1995) found a link between odd hip muscle activation patterns and hypermobile ankles. All of these studies suggest that training of the motion and motor patterns of the individual would be a wise approach.

3. Individual characteristics that constitute risk factors

A few years ago, a study examined a cohort of workers who performed similar work (McGill *et al.* 2003). They were either hydro linemen, where ergonomic job design was limited, or workers who handled metal car bumpers in a plant where ergonomic job design had been attempted – the ergonomic components of the job, for the purposes of this study, were somewhat controlled. One-third of the workers had chronic, recurrent back troubles while the others did not. Very comprehensive evaluations were performed that included measurement of psychosocial variables, physical characteristics such as strength, range of motion, endurance and then some very comprehensive measures of their motion and motor patterns while they performed a battery of tasks. Back loads were then estimated from the detailed model, described earlier, that utilised the EMG patterns of each individual to compute muscle forces and measures of spine posture to obtain passive tissue forces. In this way, individual movement patterns were recognised and assessed. Surprisingly, the chronic backs had higher strength measures. While this was initially puzzling, analysis of the mechanisms revealed they used their backs more than their healthy colleagues! They chose to move with more spine motion and activate muscle in a way that caused higher back loads. Stevenson *et al.* (2001) and Marras (2005) have made similar observations. This evidence suggests that an approach to address the cause rather than the symptoms must include ergonomics, but also to look farther and consider changing the individual.

Other studies have shown how painful backs are characterised by perturbed motion/motor patterns that perpetuate the dysfunction. The simple example of rising from a chair illustrates how the choice of pattern influences tissue load. Typically, the individual with a flexion intolerant back, characterised by recurrent acute attacks of disabling back pain, will use more spine flexion – both the present author and Professor Peter O'Sullivan's group (2004) have noted this. While still in the chair, their first spine movement is spine flexion with hip extension. As the torso rises, the hips are extended generally using the hamstrings, followed by spine extension using the extensors, which result in more loading of a bent spine. A more spine conserving pattern, and more typical of the pain-free back, is to first extend the spine and flex at the hips while still seated, while hip torque is accomplished with more gluteal muscle activity. These patterns imposed less load on the low back. Generally, and paradoxically, the painful back often moves in a way that results in more load! Many other examples exist where the personal movement strategies determine the joint load and the subsequent risk of injury.

Nearly all injury mechanisms are linked to joint motion and posture patterns. For example, posture determines which tissue is damaged and at which load (magnitude, duration, frequency, load rate, etc). In the case of disc herniation, repeated joint flexion appears to be a necessary condition (McGill 2007). If the motion is transferred to the hip, the mechanism is eliminated. Matching of injury mechanisms to movement mechanisms has led to the development of a list of guidelines that will reduce loading on the vulnerable back tissues (they formed a substantial part of this lecture (see McGill 2007)). The obvious question is whether workers can change their patterns prior to injury. Certainly, clinical work demonstrates that re-patterning movement patterns in those with painful backs is possible and works well (McGill 2006). This is an essential component in removing the cause of the painful condition so that any subsequent therapy has a chance for success. Interestingly, failure at this level is often attributed to poor therapy rather than to the failure to remove the cause of the exacerbating tissue loads.

4. What is the optimal amount of loading?

Many clinicians, engineers and ergonomists believe that reducing the risk of low back injury involves the reduction of applied loads to the various anatomical components at risk of injury. Without question, reduction of excessive loads is beneficial, but this is an overly simplistic view. Optimal tissue health requires an envelope of loading, not too much or too little. While some occupations require lower loads to reduce the risk, in sedentary occupations the risk can be better reduced with more loading and varying the nature of the loading. The problem is that the levels of optimal load, together with the failure loads, remain obscure. Of course there are general epidemiologically based studies that link injury rates with load. For example, Herrin and colleagues (1986) showed that the injury risk was doubled if the spine was exposed to compressive forces that exceeded 6800 N, although there are not many other studies that have been able to show such a relationship. This is because the relationship between loading and injury risk is probably 'U'-shaped. Too little load does not stimulate adaptation of healthy tissue while too much load causes destruction. The 'just right' load will incorporate the right magnitude, repetition, rest period and interval design, etc. A 'U'-shaped function requires many points on the curve to describe it, while a linear relationship needs only two points. Unfortunately, most studies compare light with heavy work, or neutral spine with twisting, for example, creating only two contrasting data points. Porter (1987, 1992) developed an interesting hypothesis in his study of miners who began the profession at different ages. He concluded that heavy work performed between the ages of 15–20 years was protective for future disc protrusion but predisposing for nerve entrapment syndromes. Clearly, the optimum load will be different for each person throughout their working life. The load will be determined by how they move and how they activate muscle, even independently of job design. Consider that work with power lifters showed that those who lifted closer to the world record did so with lower back loads and higher hip loads. This was determined by their skill at movement.

5. Injury mechanisms modulated by posture, motion and motor patterns

A few injury mechanisms that are influenced by the way in which a worker moves are listed below:

- End plates. End-plate fractures and Schmorl's nodes are both the result of compressive overload. Interestingly, the failure load is heavily influenced by posture, in that a flexed spine fails at much lower loads than when in a neutral posture (Gunning *et al.* 2001).
- Disc annulus. Classic disc herniation appears to be associated with repeated flexion motion with only moderate compressive loading required (Callaghan and McGill 2001) and with full flexion with lateral bending and twisting (e.g. Gordon *et al.* 1991). Recent work has documented that the location of the herniation can be predicted by the dominant motion axis (Aultman *et al.* 2005). For example, flexion but with a component of lateral bend to the right will almost guarantee that the herniation will occur posterior–lateral to the left.
- Nucleus. Too much compressive load has been shown to instigate cell apoptosis (cell death) (Lotz *et al.* 1998).
- Neural arch (posterior bony elements). Spondylitic fractures are thought to occur from repeated stress–strain reversals associated with cyclic full flexion and extension (Burnett *et al.* 1996). Cripton *et al.* (1995) and Yingling and McGill (1999) also documented that excessive shear forces can fracture parts of the arch. Shear experienced by the spine is heavily determined by lumbar curvature and the activity level of the lumbar longissimus and iliocostalis (McGill 2007).
- Ligaments. Ligaments seem to avulse at lower load rates but tear in their mid-substance at higher load rates (Noyes *et al.* 1974). McGill (1997) hypothesised that landing on the buttocks from a fall will rupture the interspinous complex given the documented forces (McGill and Callaghan 1999) and ligament tolerance when at end range of motion. Buckling during instances of spine instability may lead to strain and avulsion (McGill 2007).

Each of these mechanisms are suspected to follow the 'U'-shaped function, meaning that some loading is beneficial while too much loading causes tissue damage, cell death, etc.

6. Personal variables that modulate the risk of injury

If causes of tissue overload to the point of damage and pain have a movement pattern aetiology then the prevention approach should also include a component of corrective movement patterns together with job design. A few are briefly listed below, although a complete list for workers is in McGill (2007) and for athletes (including occupational athletes) in McGill (2006).

- Avoid end range of lumbar motion when under load – this eliminates the risk of disc damage. The risk of disc endplate fracture and annulus damage is a function of posture. Specifically, a fully flexed disc will sustain damage at a 23–43% lower load than when in a neutral posture (Gunning *et al.* 2001). This necessitates that the person flexes about the hips, with a 'hip hinge', rather than the spine (McGill 2007).
- Avoid loading immediately after prolonged flexion – the spine has a biomechanical memory. Following a period of flexion the additional laxity experienced by the spine takes a relatively long time to return (McGill and Brown 1992, Green *et al.* 2002) leaving the spine vulnerable to over bending and potentially buckling (McGill. 2007). This can be addressed by job design and task pacing or by educating the worker to stand or walk for a short period prior to lifting.
- Pre-stress the torso-spine system for stability – a spine without muscles to buttress bending will buckle under 90 N of compressive load

(Panjabi 1992); this is less than the weight of the upper body! Lightly stiffening the torso with abdominal wall cocontraction has been shown to provide sufficient stiffness and stability for many tasks when the torso is held upright (Cholewicki and McGill 1996). The instruction to the worker is to stiffen or brace the abdominal wall. The amount of stiffening/activation is tuned to the requirements of the task (see McGill 2007).

- Reduce the reaction moment on the low back – reducing the reaction moment reduces the muscularly imposed forces acting on the spine. While many conceive this as meaning holding the load close when lifting, it extends to pushing and pulling tasks as well (see next point).
- Remember the transmissible vector – the transmissible vector is the force vector applied by the worker on an object. If it does not pass through the spine, muscle forces are needed to counter the torque produced by the perpendicular moment arm from the spine to the force vector. Generating equivalent torques in the lateral bend axis can approach double the compressive load of a sagittal plane torque while twisting torques can impose four times the compressive load (McGill and Hoodless 1990, McGill 1992). This is due to the way muscles coactivate to support these non-sagittal torques. This is particularly important during push and pull tasks. It has been shown how skilled workers (compared to cohorts of graduate students) are able to pull more, with less spine load, by skilfully directing the transmissible vector (see McGill and Kavcic 2005 for health care workers, and Lett and McGill 2006 for firefighters). Once again, worker skill determines the loading and the risk of injury. In summary, direct the push or pull force through the spine to minimise spine load.
- Avoid twisting with twisting torque – twisting in of itself within moderation is probably not particularly dangerous although the individual modulating characteristics such as facet orientation and radial diameter are acknowledged (McGill 2006). Generating twisting torque within moderation when the spine is not twisted is also not usually dangerous (Drake *et al.* 2005), although the additional compressive load from the cocontraction associated with twisting torque production is acknowledged (McGill and Hoodless 1990). But the combination of generating twisting torque while being twisted is particularly of concern given the higher applied load to a structure weakened with a compromised breaking load due to the posture (see McGill 2007 for examples).
- Use skill to transfer momentum and reduce loading – even though it is popular in various work manuals, instructing workers to 'lift slowly and smoothly' reduces their joint-sparing skill. While the intent was to reduce inertial forces from simultaneous body and load acceleration, this compromises the workers' skill to transfer momentum from the body to the load to reduce joint forces (see McGill and Norman 1985, McGill 2007). The key is to generate momentum in the body first, which is then transferred to the load. Obviously, trying the 'kinetic lift' with an object on the floor, or with one that is very heavy, is contraindicated.

Several barriers exist for optimising this approach. It may be very difficult to motivate those identified with compromising patterns of movement to change. Skill is required to recognise perturbed patterns and to determine the best corrective movement and exercise approach. Further, those with an injury history may be compromised in adopting joint sparing patterns simply because of compromised joint mechanics. This individual approach, rather than a 'group ergonomics' approach, is costly but must be employed to optimise the effects of ergonomics intervention. However, evidence is beginning to emerge that the effort is effective from both a cost savings and injury rate perspective. Using a 'job coach' trained in both ergonomic approaches together with movement patterning has resulted in substantial real dollar and injury costs. More time is required to observe if the effects are lasting.

In summary, painful, disabled backs from tissue damage do not just happen, nor are they caused by psychosocial issues. In many cases, ergonomic approaches involving job design are impractical or do not address the injury mechanisms that form the root cause of disabled backs. Entire sectors of the workforce cannot use job design (in jobs such as in law enforcement, forestry, farming, fishing, to name a few). The argument made here is that optimisation of the ergonomic effort for successful reduction of back injury rates in the future will have to consider 'changing the person to fit the task' or training the way an individual moves.

To Professor Chaffin

To paraphrase Sir Isaac Newton: 'If I have been able to see over the next hill it was because I stood on the shoulders of giants before me'. Thank you, Don Chaffin, for those steady shoulders. I wish you and Barbara a wonderful retirement and peace in knowing that you have made our world a better place. My students, and those who have been similarly influenced, will continue the effort.

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