PERFORMANCE AND HEALTH CONCEPTS IN ARTISTIC GYMNASTICS

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INTRODUCTION: Artistic gymnastics attracts a large number of children and offers a range of participation levels. Gymnastics starts for many with Kindergym classes which are aimed at the development of fundamental motor skills in a game-like gymnastics environment. Most children will continue onto recreational (non competitive) gymnastics or to a nationally structured competitive program, with a select few then going onto high intensity elite training and competition from as early as 6 to 8 years of age. Considerable variability is evident in the ability of gymnasts to perform each of the apparatus during competition at all levels (inter-club, state, national, international) often due to the individual variation in physical attributes. Gymnastics requires explosive sprinting, jumping, pushing and pulling skills, together with balance and artistry on four apparatus for women (beam, uneven bars, floor, vault) and five for men (high bar, parallel bars, pommel horse, floor, vault). In competition these apparatus routines are judged subjectively by a panel of judges to identify the content and difficulty (D score) and the perfection in execution (E score).

THE CODE OF POINTS FROM A BIOMECHANICS PERSPECTIVE: The sport of gymnastics is governed by the Fédération Internationale de Gymnastique (FIG), with rules outlined for each Olympic cycle by the Code of Points (COP). The general rules and skill classifications outlined in the COP can greatly influence routine composition and therefore performance, particularly at the elite levels of gymnastics where coaches and gymnasts seek to develop a high D score. The COP can also influence the safety of the gymnasts across all levels of competition gymnastics. A recent change to the COP, for example, now requires women to stick their tumbling two foot landings on floor, without a step backwards. The COP across all apparatus for both women and men also stipulates that the feet must be held together, side-by-side when landing, with deductions for a visible gap between the feet (0.1), a step or hop (0.3), a deep squat (0.5), or a fall (1.00; FIG, 2009, p 15).

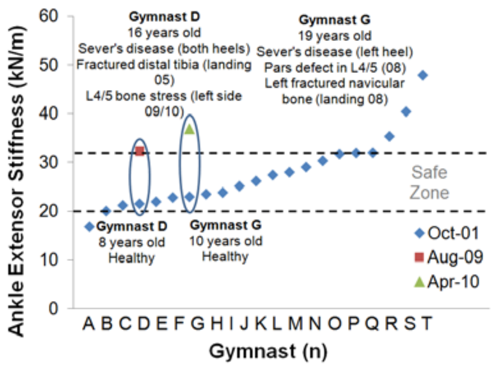
The ground reaction forces of two foot landings in gymnastics are significant during training (~5 BW) and competition (~11 BW), especially if the landing is uneven (~18 BW; Panzer *et al.*, 1988) or if there is unusual foot placement. Sticking the landing after high airborne skills requires tremendous stabilisation and eccentric strength to prevent the knee joints from collapsing (Kerin, 2006) due to the high external knee joint loads. An uneven landing or unusual foot placement can result in, for example, increased dynamic valgus knee moments (knee rotated inwards), and increases the load on the anterior cruciate ligament several-fold (Hewett *et al.*, 2005). The neuromuscular control of the centre of mass trajectory to control the body's momentum and angular rotation is also specific to the landing task, whether landing from a height without any angular rotation, or from forward or backward salto(s) (McNitt-Gray *et al.*, 2001). Wider research from other sports (e.g. netball, basketball, volleyball) has revealed that the amount of knee flexion has a greater influence on the magnitude of the impact force, than the height of the drop (Stacoff *et al.*, 1988). Ideally two foot (toe-heel) landings should be performed with even distribution of forces between the feet that are spaced roughly shoulder width apart, with actively controlled hip, knee, and ankle (plantar-) flexion with the knees over the toes (e.g. Tillman *et al.*, 2004). However the ground reaction forces in a controlled staggered landing (one foot forward) where the feet land sequentially is about half that of a traditional two foot landing. Unpublished data of 39 elite netball players landing from a high pass catch revealed landing forces of 8.2 BW (SD=±0.72) for a double foot placement, and 4.9 BW (SD=±0.13) for a staggered foot placement where one foot lands sequentially in front of the other. Whilst the recent change to the COP specifically for women's floor tumbling landings is unfortunate from a coach and gymnasts perspective (Black, 2009), greater biomechanical exploration is required to determine whether an additional step after a two foot landing does produce lower ground reaction forces. Any change to the COP must be done with caution in order to maximise safety for the competitors and to remain sensitive to the history and tradition of gymnastics.

POSITIVE AND NEGATIVE EFFECTS OF IMPACT IN GYMNASTICS: The skills necessary to compete in gymnastics require both upper and lower limb weight bearing. There are both negative and positive effects of this weight bearing impact.

The extreme forces placed on the gymnasts' body in combination with the repetitive movements and high training hours are more than likely a major factor behind the reportedly high incidence of injuries (Lilley, 2006). Although the types of injuries sustained in gymnastics are comparable with many other sports, gymnastics is unique in that the gymnasts receive the majority of their training during their childhood years (Sands, 2000). The lower extremities have been identified as the most likely anatomical location to sustain injuries (72%). The ankle has the highest reported injuries with 48% occurring during landings and 36% during take-off. The upper limbs, followed by the spine and trunk are the next most frequent sites of injury (Kirilanis *et al.*, 2003). During training, a preferred leg and hand often develops when aiming to achieve performance consistency and reliability of a skill. This can lead to a potential functional imbalance between the limbs. In non-elite competitive gymnasts (National Levels 4-6), Lilley *et al.* (2007) identified only two gymnasts out of 15 who had functionally symmetrical landings (less than 10% difference between limbs; Grace, 1985) with one gymnast having a staggering 73% of asymmetry ($\overline{X}$ = 18.14$\pm$20.46%). Recent unpublished results of 25 international development stream (elite) gymnasts performing drop landings from heights of 70 and 95 cm revealed a more favourable result, with 11 of the 25 gymnasts displaying functionally symmetrical landings ($\overline{X}$ = 6.85$\pm$14.59%, Max=32.74%) and much lower overall levels of asymmetry. Attenuating more force on one leg amplifies the risk to gymnasts of sustaining a chronic overuse injury, and is one of the most common means of injury in other sports (Kovacs *et al.*, 1999). Reduced knee flexion (Stacoff *et al.*, 1988), unusual foot placement, and increased leg stiffness (Bradshaw *et al.*, 2006; Butler *et al.*, 2003) are other potential contributing factors.

Retrospective analyses of ankle stiffness measures of self-paced double legged hopping by Bradshaw *et al.*, (2006) revealed a potential safe zone for ankle injury. As shown in Figure 1, the gymnast (A) with low stiffness had previously suffered a landing ankle injury, and four gymnasts (P, R, S, T) with high stiffness had medical histories of take-off ankle injuries such as Achilles tendonitis. A recent unpublished follow-up of two of the gymnasts (D, G) from the original study, who were still training eight years later, revealed that their ankle extensor stiffness had increased by 10.78 and 13.93 kN/m respectively. Both of the gymnasts reported Sever's disease (calcaneal apophysitis due to overuse and repetitive microtrauma of growth plates of the calcaneus in the heel) in one or both heels, and lower lumbar spine stress such as pars defect. The altered ankle extensor stiffness of these two gymnasts in combination with the reported injuries indicates that this biomechanical test has potential for monitoring injury risk, especially during peak growth years, and requires further research. Achilles strain measures using ultrasonography during a ramped protocol (three different loads) of isometric calf raises (Bryant *et al.*, 2008) may provide a further potential screening tool in gymnastics populations.

Figure 1. Ankle extensor stiffness measured from a series of six double legged hops with the knees held in an extended position from Bradshaw *et al*. (2006), with follow-up data on gymnast D and G.



Whilst there is considerable focus upon the extreme impact forces in gymnastics, the broad spectrum of loading through gymnastics participation also has many positive effects that include increased bone mass and reduced risk of osteoporosis later in life. Highly active adolescent gymnasts (n=25) have been recently shown by Greene *et al.* (2009) to display greater trabecular density, trabecular area, and bone strength at the 4% distal tibial site ($p<0.001$) and the distal radius ($p<0.001$), when compared to aged matched track and field athletes (n=34), water polo athletes (n=30), and less active controls (n=28) (Greene *et al.*, 2009). The trabecular bone tissue (the porous, spongy bone) is believed to be the most responsive to strain through loading activity (Huickes *et al.*, 2000). However despite the much lower training hours of track and field athletes ($\overline{X}$ = 8.4$\pm$3.9 hrs) when compared to gymnasts ($\overline{X}$ = 33.2$\pm$2.3 hrs), those athletes were superior to gymnasts for tibial cortical (the solid, outer layer of compact bone tissue) bone area and strength (measured at 14, 38, and 66% distal site), and may therefore have a correspondingly lower stress fracture risk (Wachter *et al.,* 2002). These skeletal responses may be due in part to the significantly differing overall calf size (girth), and also the differing sports surfaces for training and competition in gymnastics and athletics. Some cross-training on athletic surfaces such as running and targeting drills for vaulting, and general physical training may advantage a gymnast by increasing their cortical bone strength and reducing their overall fracture risk.

BIOMECHANICAL INFLUENCES ON TRAINING: Monitoring training objectively, with the exception of qualitative video feedback, in gymnastics is not routinely part of the sport with few known exceptions such as the Men's National Training Centre in Germany (Nissenen, 2007). This differs to other sports such as track and field and swimming where access to an instrumented track is particularly common, with swimming flumes and instrumented pools also available. Bradshaw *et al.* (2009) developed a vault timing system that measured the approach velocity through to beat board contact reliably during regular vault training of elite gymnasts. Pre-flight and table contact time were revealed to be not reliable in a training situation, but may be more reliable when used as part of monthly control (pure repeat) testing. Other researchers have attempted to instrument the apparatus such as the men's rings and high bar (e.g. Sands *et al.*, 2006) however it is unknown whether these scientific tools are used regularly in training.

Often the most important test of biomechanical research is whether it eventually improves performance and/or influences coaching (and training) practice through increased knowledge. One study that achieved success in Australia was that on target-directed running in vaulting (Bradshaw, 2004). It revealed that gymnasts' who want to perform more advanced vaults, need to be able to target and adjust their strides early in the approach in order to hit the beat board with high velocity. This is similar to the run-up skills required in long jumping (Bradshaw & Aisbett, 2006). A quote below provides a summary on how the study impacted gymnastics in Australia from the state coaches' perspective:

> "The vault targeting study was of great use to athlete and coaches. Vaulting is about hitting a target at the greatest possible controlled speed; the best vaulters in the world have the best speed. You then look at ways to develop speed, normally strength work and running and jumping drills. As a coach you want to develop this as quickly as possible so you end up with acceptable speeds and good vaults but there is always a nagging question that something is missing to get optimal performance. There are many cases where the athlete is no longer confident with their run and try to adjust where they start from. The adaptation from the training gym to podium performances where the run-up surfaces are totally different provides continual problems and need for adjustment. Enter the *Biomechanist* and a concept of targeting. We all know that the gymnast runs at a target, but have had no real idea how they do this except by the adjustment of the run up until we get something comfortable and have good speed; a long process. Liz's study of targeting in vaulting has led to a total change in the way the run and jump (take-off) is taught, and the way the significant problem of the lost run-up is viewed and dealt with. The better athletes target much earlier, the poorer and beginner ones later. This was able to be determined through non-invasive video analysis in a practical situation with a variety of level of athlete. The results from this expanded the focus of coaching vault. Drills specifically for

targeting are now included and problems with run ups are generally put into the area of an inability to target. Liz not only conducted the analysis but was also able provide drills and methodology to teach athletes to target." (Mark Calton, 11/6/2007).

Whilst there is a vast array of good quality research on gymnastics (e.g. Hiley & Yeadon, 2005; Irwin *et al.*, 2005), further fundamental research that exhibits great promise for influencing coaching (and training) practice is that of computer simulation forward modelling. This is because coaches with gymnasts seeking the epitome of competition performance are always seeking to know how to push skills further, such as the number of saltos and/or twists that can be successfully performed on floor or vault. Forward modelling such as Yeadon's (2009) simulation of the aerial skiing triple and quadruple twisting performance begins to provide information on the take-off velocity and technique required to accomplish these feats. Eventually this method of biomechanical enquiry should begin to impact upon the upper levels of elite gymnastics training.

CONCLUSION: Research on gymnastics has predominantly been focused upon the high performance participation levels, with quantitative descriptions of specific skills (e.g. Takei *et al.*, 2000), as well as epidemiological reports on injury rates, and on the impact of committed training on growth (e.g. Caine *et al.*, 2003). From a performance perspective this fails to address fundamental issues that could be broadly applied during training. Further, from an injury prevention perspective greater focus is required on the elementary years of gymnastics when the fundamental motor skills are being formed (e.g. jumping and landing), and also on the lower to middle competitive levels that involves the bulk of participants and similar rates of injury (Kolt & Kirkby, 1999). Therefore to monitor and enhance the performance of all gymnasts, key elements that maximise technique and safety need to be identified. Biomechanics can help improve gymnastics performance and reduce injury risk to provide a positive participation and/or competition experience. Research that addresses fundamental issues in gymnastics that can influence the performance of gymnasts and/or the knowledge of the coaches (e.g. Bradshaw, 2004), or can prevent injury (e.g. Bradshaw *et al.*, 2006) has provided these avenues. A wider perspective of the sport (e.g. general articles in the Code of Points), and by using techniques and knowledge developed by other scientific disciplines (e.g. motor control, engineering) can further enhance the influence of biomechanics on this sport in the future.

REFERENCES:

Black, D. (2009). Judging judges. *International Gymnast*, Norman; OK, USA, December, 48.

Bradshaw, E.J. (2004). Target-directed running in gymnastics: A preliminary exploration of vaulting. *Sport Biomechanics*, **3**, 125-144.

Bradshaw, E.J. & Aisbett, B. (2006). Visual guidance during competition performance and run-through training in long jumping. *Sport Biomechanics*, **5**, 1-14.

Bradshaw, E. J., Le Rossignol, P., Williams, M., Lorenzen, C. (2006). Novel insights on lower limb musculoskeletal health and performance in pre-adolescent and adolescent gymnasts. In; Schwameder, H., Strutzenberger, G., Fastenbauer, V., Lindinger, S., Muller, E. (Eds). *XXIV International Symposium on Biomechanics in Sports Proceedings*, University of Salzburg, Salzburg, 14-18 July, 413-417.

Bradshaw, Elizabeth J., Hume, Patria A., Calton, Mark, Aisbett, Brad, (2009). Reliability of a gymnastics vaulting system. In: Harrison, D., Anderson, R., Kenny, I. (Eds), *XXVII International Conference on Biomechanics in Sports Proceedings*, University of Limerick, Limerick, 17-21 August, 223-226.

Bryant, A., Clark, R., Bartold, S., Murphy, A., Bennell, K., Hohmann, E., Marshall-Gradisnik, S., Payne, C., Crossley, K.M. (2008). Effects of estrogen on the mechanical behaviour of the human Achilles tendon in vivo. *Journal of Applied Physiology*, **105**, 1035-1043.

Butler, R.J., Cowell, H.P., McClay Davis, I. (2003). Lower extremity stiffness: Implications for performance and injury. *Clinical Biomechanics*, **18**, 511-517.

Caine, D., Bass, S.L., Daly, R. (2003). Does elite competition inhibit growth and delay maturation in some gymnasts? Quite possibly. *Pediatric Exercise Science*, **15**, 360-372.

Fédération Internationale De Gymnastique (1999). *2009 Code of Points — Women's Artistic Gymnastics*. Women's Technical Committee, FIG, Switzerland.

Grace, T. G. (1985). Muscle imbalance and extremity injury. *Journal of Sports Medicine,* **2**, 77.
Greene D. A, Naughton, G. A., Bradshaw, E., Moresi, M. (2009) Musculoskeletal profile of elite adolescent female athletes in weight-loaded and weight-supported sports. *American College of Sports Medicine Conference*, Seattle, USA, 27-30 May, 2250.
Hewett, T.E., Myer, G.D., Ford, K.R., Heidt, R.S., 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. *The American Journal of Sports Medicine*, **33**, 492-501.
Hiley, M.J. & Yeadon, M.R. (2005). The margin for error when releasing the asymmetric bars for dismounts. *Journal of Applied Biomechanics*, **21**, 223-235.
Huiskes, R., Rulmermann, R., van Lenthe, G.H., Janssen, J.D. (2000). Effects of mechanical forces on maintenance and adaptation of form in trabecular bone. *Nature*, **405**, 704-706.
Irwin, G., Hanton, S., Kerwin, D.G. (2005). The conceptual process of skill progression development in artistic gymnastics. *Journal of Sports Sciences,* **23**, 1089-1099.
Kerin, D. (2006). *What is the most direct means to achieve strength gains specific to the demands of jumping events?* Middlebury, VT, USA: Middlebury College.
Kirialanis, P., Malliou, P., Beneka, A., & Giannakopoulos, K. (2003). Occurrence of acute lower limb injuries in artistic gymnasts in relation to event and exercise phase. *British Journal of Sports Medicine,* **37**(2), 137-139.
Kolt, G.S. & Kirkby, R.J. (1999). Epidemiology of injury in elite and subelite female gymnasts: a comparison of retrospective and prospective findings. *British Journal of Sports Medicine*, **33**, 312-318.
Kovacs, I., Tihanyi, J., DeVita, P., Racz, L., Barrier, J., Hortobagyi, T. (1999). Foot placement modifies kinematics and kinetics during drop jumping. *Medicine and Science in Sports and Exercise,* **31**, 708-716.
Lilly, E. (2006). *Bilateral lower extremity performance safety in pre-adolescent and adolescent competitive gymnasts*. Melbourne, Victoria, Australia: Australian Catholic University.
Lilley, E.S., Bradshaw, E.J., Rice, V.J. (2007). Is jumping and landing technique symmetrical in female gymnasts?. In; Menzel, H-J., & Chagas, M.H. (Ed). *XXV International Symposium on Biomechanics in Sports Proceedings*, Federal University of the State of Minas Gerais in Belo Horizonte, Ouro Preto, 23-27 August, 345-348.
McNitt-Gray, J.L., Hester, D.M.E., Mathiyakom, W., Munkasy, B.A. (2001). Mechanical demand and multijoint control during landing depend on orientation of the body segments relative to the reaction force. *Journal of Biomechanics*, **34**, 1471–1482.
Nissenen, M. (2007). Longterm biomechanical performance diagnostics with the German national gymnastics team. In; Menzel, H-J., & Chagas, M.H. (Ed). *XXV International Symposium on Biomechanics in Sports*, Federal University of the State of Minas Gerais in Belo Horizonte, Ouro Preto, 23-27 August, 8.
Panzer, V. P., Wood, G. A., Bates, T. B., Mason, B. R. (1988). Lower extremity loads in landings of elite gymnasts. In: De Groot, G., Hollander, A.P., Huijing, P.A., Van Ingen Schenau, G.J. (Eds). *Biomechanics XI*, Free University Press, Amsterdam, The Netherlands, 701-704.
Sands, W. A. (2000). Injury Prevention in Womens Gymnastics. *Sports Medicine,* **30**(5), 359 - 373.
Sands, W.A., Stone, M.H., McNeal, J.R., Smith, S.L., Jemni, M., Dunlavy, J.K., Mizushima, K., Haff, G.G. (2006). A pilot study to measure force development during a simulated maltese cross for gymnastics still rings. In; Schwameder, H., Strutzenberger, G., Fastenbauer, V., Lindinger, S., Muller, E. (Eds). *XXIV International Symposium on Biomechanics in Sports Proceedings*, University of Salzburg, Salzburg, 14-18 July, 404-407.
Stacoff, A., Kaelin, X. and Stuessi, E. (1988) The impact in landing after a volleyball block. In; *Biomechanics XI-B*. Amsterdam, The Netherlands: Free University Press, 694-700.
Takei, Y., Blucker, E.P., Nohara, H., Yamashita, N. (2000). The Hecht vault performed at the 1995 world gymnastics championships: Deterministic model and judge's scores. *Journal of Sports Sciences*, **18**, 849-863.
Tillman, M.D., Hass, C.J., Brunt, D., Bennett, G.R. (2004). Jumping and landing techniques in elite women’s volleyball. *Journal of Sports Science and Medicine*, **3**, 30-36.
Wachter, N.J., Krischak, G.D., Mentzel, M., Sarkar, M.R., Ebinger, T., Kinzl, L., Claes, L., Augat, P. (2002). Correlation of bone mineral density with strength and microstructural parameters of corticol bone in vitro. *Bone*, **31**, 90-95.
Yeadon, M.R. (2009). Application of simulation to freestyle aerial skiing. In: Harrison, D., Anderson, R., Kenny, I. (Eds), *XXVII International Conference on Biomechanics in Sports Proceedings*, University of Limerick, Limerick, 17-21 August, 117-120.