Institution: Nottingham Trent University (NTU)		
Unit of Assessment: C24 – Sport and Exercise Science, Leisure and Tourism		
Title of case study: Changing nutritional and training practices to improve the bone health of elite athletes and sports people internationally.		
Period when the underpinning research was undertaken: 2010 - present.		
Details of staff conducting the underpinning research from the submitting unit:		
Names:	**Roles:**	**Periods employed by submitting HEI:**
Craig Sale	Professor	2008-present
Kirsty Elliott-Sale	Associate Professor	2010-present
Ian Varley	Lecturer	2014-present
Period when the claimed impact occurred: January 2014 – July 31, 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Poor bone health in athletes increases the risk of long-term injuries, limits performance and is a significant drain on resources. Through proactive engagement with national sports institutes and leading sports teams, our research into the impact of nutrition and exercise on bone health has made a key contribution to reducing the injury burden for elite athletes internationally, including in high-profile Olympic sports. As a result of changes to dietary and training behaviours implemented because of our research, impact can be demonstrated in five areas:

1) Contribution to a reduction in bone stress injuries for Britain's world-leading triathletes.
2) Development of nutritional strategies to improve bone health across national athletics teams in Britain, Ireland, Canada and New Zealand.
3) Contribution to reduced rates of injury and improved performance within New Zealand's elite women's rowing team.
4) Reductions in bone-related injuries among 310 players from first team to academy level at two English football clubs.
5) Increasing awareness and understanding of bone health among elite cricketers.

2. Underpinning research

The maintenance of an injury-free athlete is integral to individual and team successes in elite sport. As an estimate, around fifty elite British track and field athletes suffer from bone injuries each year, equating to 11% of all injuries lasting longer than two weeks, with a similar pattern of injury being indicated worldwide.

Much of NTU's research has focused upon bone (re)modelling, a process whereby older bone tissue is removed from the skeleton (bone resorption) and new bone tissue is formed (bone formation). The balance between bone resorption and formation helps the skeleton to respond to mechanical loading and to microdamage and injuries. Supported by funding from the English Institute of Sport (EIS) and the Ministry of Defence (MOD), research within the Musculoskeletal Physiology Research Group of the Sport, Health and Performance Enhancement Research Centre at NTU has, since 2008, sought to develop novel dietary and training strategies that can improve bone health and reduce injury risk in elite athletes, military personnel and athletic individuals, with this case study focussing upon the impact delivered in elite athletes. It began with a series of studies, published in collaboration with QinetiQ Ltd that showed, for the first time, that strenuous exercise increased bone resorption for at least four days after exercise in endurance trained and recreationally active individuals. This short-term alteration in bone metabolism is a factor in the development of stress fracture injury, and so Sale and colleagues embarked upon a long-term research programme to explore ways to moderate the bone metabolic response to exercise and reduce the risk of bone injuries.

The studies with QinetiQ Ltd had also examined the effects of feeding versus fasting and showed that whilst feeding initially reduced markers of bone resorption in advance of exercise, there was no lasting effect once exercise commenced (Scott et al., 2012, *Bone*, 51, 990-999). A further study, commissioned by the Army Recruiting and Training Division (ARTD) and led by Sale (**G1**) showed that feeding carbohydrate during exercise could reduce, at least in the short-term, the negative effects of hard exercise on the bone (**R1**). Building upon this work, collaborative research, involving Sale and led by Liverpool John Moores University, further indicated the importance of

carbohydrate availability, showing that consuming carbohydrate before, during and after high-intensity intermittent running attenuated the bone resorption response independent of energy availability (**R2**).

A concurrent strand of research in collaboration with British Triathlon, co-funded by the English Institute of Sport (EIS) (**G2**), highlighted the acute effects of strenuous exercise on bone metabolism and identified time points where the risk to bone health was at its greatest during training. Interventions were designed to mitigate these risks and optimise performance. NTU researchers examined the bone (re)modelling marker responses of elite triathletes to one week of typical training at two different points of their season and recorded bone (re)modelling rates well above those of sedentary and recreationally active individuals, which might have been explained by reduced micronutrient intakes (predominantly calcium) and under-fuelling. It is likely that this contributed to the fact that 75% of these athletes had suffered a stress fracture injury during their careers, with some having a history of multiple stress fractures. In a follow-up, NTU analysed the effects of post-exercise protein and carbohydrate feeding on the bone response in recovery. This showed that the immediate ingestion of carbohydrate and protein decreased bone resorption and increased bone formation (**R3**), potentially creating a more positive bone turnover balance and providing a strategy to help reduce injury risk in elite endurance athletes.

NTU-led research into reduced energy availability and bone (re)modelling has indicated that women might be more susceptible to negative bone consequences than men (**R4**). It has also shown that dietary restriction might be a more powerful stimulus for this than increases in exercise energy expenditure, further confirming the importance of an athlete's diet in protecting the bone during hard exercise (**R5**).

Research led by NTU investigated tibial bone adaptations in response to 12 weeks of increased training volume in elite adolescent football players. It showed that high-impact, multi-directional movement improved bone density (**R6**). However, the study also indicated that the stimulus required for this might be close to the fracture threshold of bone in some individuals, possibly increasing bone injury risk. Further funding is supporting work relating to factors involved in the development of musculoskeletal injury (**G3**).

3. References to the research

Underpinning research quality evidenced by rigorously externally peer reviewed outputs:

R1. Sale, C., Varley, I., Jones, T.W., James, R.M., Tang, J.C.Y., Fraser, W.D., and Greeves, J.P. (2015). Effect of Carbohydrate Feeding on the Bone Metabolic Response to Exhaustive Running. *Journal of Applied Physiology*, 119(7), 824-30. DOI: 10.1152/japplphysiol.00241.2015.

R2. Hammond, K.M., Sale, C., Fraser, W.D., Tang, J., Shepherd, S.O., Strauss, J.A., Close, G.L., Cocks, M., Louis, J., Pugh, J., Stewart, C., Sharples, A.P. and Morton, J.P. (2019). Post-exercise carbohydrate and energy availability induce independent effects on skeletal muscle cell signalling and bone turnover: implications for training adaptation. *Journal of Physiology*, 597(18), 4779-4796. DOI: 10.1113/JP278209

R3. Townsend, R., Elliott-Sale, K.J., Currell, K., Tang, J., Fraser, W.D. and Sale, C. (2017). Post-Exercise Ingestion of Carbohydrate and Protein Suppresses Bone Resorption. *Medicine & Science in Sports & Exercise*, 49(6), 1209-1218. DOI: 10.1249/MSS.0000000000001211.

R4. Papageorgiou, M., Elliott-Sale, K.J., Parsons, A., Tang, J., Greeves, J.P., Fraser, W.D. and Sale, C. (2017). Effects of reduced energy availability on bone metabolism in men and women. *Bone*, 105, 191-199. DOI: 10.1016/j.bone.2017.08.019.

R5. Papageorgiou, M., Martin, D., Colgan, H., Cooper, C., Greeves, J.P., Tang, J.C.Y., Fraser, W.D., Elliott-Sale, K.J. and Sale, C. (2018). Bone metabolic responses to low energy availability achieved by diet or exercise in active eumenorrheic women. *Bone*, 114, 181-188. DOI: 10.1016/j.bone.2018.06.016.

R6. Varley, I., Hughes, D.C., Greeves, J.P., Fraser, W.D. and Sale, C. (2017). Increased training volume results in improved bone density, cross-sectional area and strength in elite adolescent footballers. *International Journal of Sports Medicine*, 38(5), 341-346. DOI: 10.1055/s-0042-124510.

The high quality of the underpinning research is further indicated by the range of funding organisations that have invested in the research and its dissemination:

G1. £15,000 grant from UK Ministry of Defence supported the carbohydrate feeding study.
G2. £33,500 in grant income received from the English Institute of Sport to support work relating to the effects of nutrition on bone health in elite endurance athletes.
G3. £940,677 UK Ministry of Defence (Army) grant, supporting work on efficacy of a postpartum physical development programme on occupational physical performance and musculoskeletal health.

4. Details of the impact

More than a decade of research at NTU into the effects of nutrition and exercise on bone health has led to changes in dietary behaviour and the development of new training strategies for elite athletes and sports teams around the world. These interventions have contributed to reductions in injury risk and resultant increases in competitive performance.

Impact 1: Contributing to a reduction in the incidence of bone stress injury among world-leading British triathletes through diet changes and education in enhancing bone health

Since 2016, NTU Musculoskeletal Physiology Research Group's research (**G2**) has resulted in improved pre-training nutrition plans, calcium intakes and ride fuelling in elite triathletes. Prior to our research, the English Institute of Sport (EIS) had no information on the impact of large training volumes and fuelling on bone (**S1**) and the data generated were used to educate the triathletes on the importance of fuelling during training, particularly on the bike, in order to consume enough energy to replace losses. The athlete-specific data provided by NTU was used to support calcium supplementation practices to meet individual requirements and to adjust the timing of training sessions. Our research (**R3**, **G2**) also prompted the development and use of carbohydrate and protein recovery drinks by British Triathlon, with, for example, 12 British Olympic triathletes using them daily during an altitude training camp prior to a successful Olympic Games in Rio 2016 (one gold, one silver, one bronze and one fourth place). Overall, our research has enabled '*positive behavioural changes*' among the triathletes '*during what can be a stressful time for those competing*' (**S1**).

The EIS reported that NTU research was used across the organisation's network, with a member of the Performance Nutrition team writing that NTU research data has been used within infographics '*to educate athletes, practitioners and coaches on the best nutritional practice to enhance bone health, which also means that nutrition is now something that is immediately addressed when an athlete presents with a bone injury* (**S1**).' The overarching benefit was summarised as: '*The power of having data on our own athletes also improved athlete adherence and helped evoke positive behaviour change. This programme of work, along with other interventions initiated within the triathlon programme has reduced bone stress injuries across the programme. Bone stress injuries are no longer the biggest time loss injury within triathlon* (**S1**).' Key to this was the fact that the NTU research (**R3**, **G2**) was developed in partnership with British Triathlon and the EIS, and was conducted on 24 elite British triathletes enrolled on the British Triathlon Performance Programme. Our approach was informed by regular consultation with the performance nutrition team and triathlon coaches, which allowed for direct translation to ensure maximum impact.

Impact 2: Informing practical nutritional strategies to improve bone health in athletics across Great Britain, Ireland, Canada, and New Zealand

NTU Musculoskeletal Physiology Research Group's research has improved nutrition practices within British Athletics (**S2**), who have engaged with NTU research through the work detailed in impact 1 and at conferences, meetings and CPD events. The studies on carbohydrate (**R1**, **G1**) and carbohydrate plus protein (**R2**, **G2**) feeding were used to increase carbohydrate ingestion during specific sessions, and promote carbohydrate and protein ingestion during recovery from hard training to facilitate positive adaptations in bone. NTU data on low energy availability (**R4**) were used to educate athletes on the negative implications of this practice for bone health. Specifically citing NTU's underpinning research publications (**R1**, **R3**, **R4**, **R5**), a Performance Nutritionist for British Athletics confirmed that the studies have informed the practical nutritional strategies employed with elite endurance runners, sprinters and cyclists (including 68 world class programme Olympic athletes, approximately 25% or whom were Olympic or World Championship medallists and or European Champions). Whilst acknowledging the difficulty in quantifying the exact effect of research-based nutritional recommendations amid other factors, he wrote: '*We*

have found positive impact from devising our nutritional strategies in accordance with the above information (i.e. carbohydrates during exercise and carbohydrate + protein post-exercise) as we have found a considerably lower number of stress fracture incidences this season (2019-2020) *compared to previous (only 1 athlete suffered a significant stress fracture compared to 3 previously)*.' (**S2**)

The High Performance Sport New Zealand (HPSNZ) Technical Lead for Performance Nutrition confirmed that they have revised and adjusted nutrition protocols and incorporated NTU research to develop educational messages, standards and guidelines for coaches and athletes, especially around the issue of low energy availability (**R4**, **R5**). The same Technical Lead at HPSNZ reported that '*As a result of NTU research we have maintained a heightened awareness of the importance of bone health with this filtering down to both the domestic and elite environment and translated into the public health area*' (**S3**).

The Canadian Sport Institute (CSI) Pacific Director of Performance Solutions said that the research of Sale and Elliot-Sale at NTU has '*contributed greatly to our understanding of bone metabolism, energy availability and health and performance outcomes*' (**S4**). For example, of the 314 Canadian athletes at the 2016 Rio Olympics, around 150 are estimated to have had some issues surrounding low energy availability or stress fracture injuries that had impacted their preparations over the previous years. CSI Pacific's Director of Performance Solutions reported that, since 2014, the research has enabled them to now show and demonstrate evidence to the coaches and athletes (gymnasts, track and field athletes, triathletes) on the negative impacts of low energy availability in order to change education and culture, with the aim of prolonging careers and health (**S4**).

The Irish Institute of Sport (IIS) adapted nutritional timing and recovery strategies for its athletes to ensure that specific nutrients are available at the time of consumption, specifically citing references (**R3**, **R4**, **R5**) among others. These adaptations have delivered improvements in terms of athlete recovery and bone density (**S5**). The Head of Performance Nutrition for IIS confirmed the significance of the overarching benefit: '*Prior to this research, we found a significant number of athletes were presenting problems in relation to energy availability and reduced CHO intakes. 'By applying these concepts into practice, we have found more training that is consistent, and less time lost in training for athletes, which then allows us better adaptations of body composition without having risky side effects of bone injuries* (**S5**).' These benefits have been delivered via education materials delivered to athletes (**S5**), which have been based upon a recent review paper from NTU's Musculoskeletal Physiology Research Group that directly references our original research (**R1**, **R3**, **R4**, **R5**).

Impact 3: Contributing reductions in bone injury rate and performance improvements in elite female rowers in New Zealand through changes to dietary and training behaviours

NTU Musculoskeletal Physiology Research Group's research on energy availability and refueling (**R1**, **R3**, **R4**, **R5**) informed the development of new educational strategies and expert advice provided by High Performance Sport New Zealand (HPSNZ) to elite female athletes in the Rowing New Zealand squad from November 2018. The HPSNZ Performance Nutrition Lead reported "*I used the knowledge gained of the research done at Nottingham Trent University to add to behaviour changes with my athletes*" (**S6**). The energy availability of the majority of athletes was less than 30 kcal/kgLBM/d before the educational materials were provided; post education the majority of athletes had improved above this level, supporting their bone health. The HPSNZ Performance Nutrition Lead confirmed that '*we managed to change behaviour that led to for example but not limited to better fueling, better recovery, better ability to back up training sessions, decreased injury rate (rib stress fractures), decreased issues with immunity and improved mood*' (**S6**). As well as decreasing time out of the boat, '*the performances of most athletes were improved from the previous year*' (**S6**).

Impact 4: Achieving reductions in bone related injuries for Everton and Nottingham Forest English football clubs through changes to dietary and training behaviours

Everton FC changed dietary strategies (feeding before and after training and supplementing with collagen and calcium) during times of increased training load (*e.g.*, during pre-season) based upon NTU research and presentations of the findings by Elliott-Sale. The Club's First Team Nutritionist

commented "*At Everton, we have had eighteen bone related injuries (1st team through to academy ~180 players) in the previous season including stress fractures and breaks*" and, citing papers (**R3**) and (**R5**) specifically, confirmed that NTU research had helped the club evaluate their practice and implement changed strategies with the result that "*during this season and so far, hugely reduced the number of bone related injuries that have occurred to two. The amount of days lost to training and thus money wasted on wages has reduced significantly*" (**S7**).

Having collaborated with Varley since 2014, Nottingham Forest Football Club used NTU research data in relation to bone adaptation over the course of a season (**R6**) to change their training practices for 30 first-team players and 100 academy players, beginning in the 2012/2013 and 2013/2014 seasons. The Club's First Team Sports Scientist wrote: '*Since these practices have been undertaken, our incidence of bone stress injuries has decreased significantly. Specifically, during the offseason & preseason we now use multi directional strength and low-level plyometrics in order to preload and subsequently best mitigate against significant increases in load come the most intense periods of preseason*' (**S8**).

Impact 5: NTU research has led to changed dietary and training behaviours and has informed educational material around bone health in English elite cricketers, coaches and practitioners.

English County Cricket, England cricketers and cricket coaches have changed the dietary and nutritional practices of players as a result of NTU research (**R1**, **R2**, **R3**, **R4**, **R5**) and discussions with the Performance Nutritionist (**S9**) at CPD meetings since 2017. Research has been presented by Sale to over 200 delegates from the cricketing world (including coaches, team managers and practitioners) at the England and Wales Cricket Board National Conference. The Performance Nutritionist for Great Britain Hockey and England Cricket confirmed, "*Following the data presented at the ECB national conference by Prof. Sale over a third of counties have now implemented Vitamin D screening for players. The use of this information across the sport has allowed us to increase the number of nutritionists working at England level to two, within counties to three practitioners to support nutrition and bone health*" (**S9**). NTU research has formed the basis of a bone health healing protocol developed by England Cricket and their implementation of specific post-exercise strategies aligned to protein and carbohydrate feeding (based upon (**R3**, **G2**)). NTU research and associated information is being used to improve coach and practitioner education as part of the ECB level 4 coaching qualification, which now includes a module on nutrition and a specific section on bone health.

5. Sources to corroborate the impact

(*participant in the process of impact delivery)

S1*. Testimonial letter: Performance Nutritionist, British Triathlon and English Institute of Sport.
S2*. Testimonial letter: Performance Nutritionist, British Athletics and English Institute of Sport.
S3*. Testimonial letter: Technical Lead Performance Nutrition, High Performance Sport New Zealand.
S4*. Testimonial letter: Director Performance Solutions at Canadian Sport Institute Pacific.
S5*. Testimonial letter: Head of Performance Nutrition at Irish Institute of Sport.
S6*. Testimonial letter: Senior Performance Nutritionist, High Performance Sport New Zealand.
S7*. Testimonial letter: First Team Nutritionist, Everton Football Club.
S8*. Testimonial letter: First Team Sports Scientist, Nottingham Forest Football Club.
S9*. Testimonial letter: Performance Nutritionist, Great Britain Hockey and England Cricket.