Tri-axial loading response to anti-gravity running highlights movement strategy compensations during knee injury rehabilitation of a professional soccer player.

Matt Greig[1], Liam Mason[2], Andy Mitchell[3]

1. Sports Injuries Research Group, Edge Hill University, Ormskirk, UK
2. Newcastle United Football Club, Sport Science Department, Newcastle, UK
3. RB Leipzig Football Club, Medical Department, Leipzig, Germany

Corresponding Author: Professor Matt Greig
Sports Injuries Research Group,
Dept. of Sport & Physical Activity
Edge Hill University
Ormskirk, L40 7AF, United Kingdom
Email: matt.greig@edgehill.ac.uk Tel: (+44) 1695 584848
ORCID-ID: 0000-0002-7315-6968

Abstract

Anti-gravity treadmills have been used in rehabilitation to manipulate exposure to loading and to prescribe return to outside running. Analysis is typically restricted to the vertical plane, but tri-axial accelerometry facilitates multi-planar analysis with relevance to injury mechanism. In this case a professional male soccer player, 4 weeks post-operative surgery to repair a medial meniscectomy, 8 months after ACL reconstruction to the same knee, completed anti-gravity treadmill running at 70-95% bodyweight (BW) at 5% increments. Tri-axial accelerometers were placed proximal to the Achilles tendon of the injured and healthy leg, and at C7. The planar acceleration at touchdown highlighted an increase at 85%BW, identifying 70% and 85%BW as discrete loading progressions. C7 (3.21 ± 0.68 $m \cdot s^{-2}$) elicited lower ($P<0.001$) vertical acceleration than the lower limb (9.31 ± 1.82 $m \cdot s^{-2}$), with no difference between limbs suggesting bilateral symmetry. However, in the medio-lateral plane the affected limb (-0.15 ± 1.82 $m \cdot s^{-2}$) was exposed to lower ($P=0.001$) medio-lateral acceleration than the non-affected limb (2.92 ± 1.35 $m \cdot s^{-2}$) at touchdown, indicative of bilateral asymmetry. PlayerLoad during foot contact was sensitive to accelerometer location, with the affected limb exposed to greater loading in all planes ($P \leq 0.082$), exacerbated at 90-95%BW. Tri-axial accelerometry provides a means of assessing multi-planar loading during rehabilitation, enhancing objective progression.

Keywords: anti-gravity treadmill, rehabilitation, soccer, accelerometry

Introduction

Progressive exposure to weight-bearing activity is a fundamental element of rehabilitation for many lower extremity injuries. Reduced or anti-gravity treadmills allow for the prescriptive manipulation of lower extremity weight-bearing load, potentially facilitating an earlier return to running activities in rehabilitation and enhance post-operative recovery (Eastlack et al., 2005; Hambly et al., 2017). The magnitude of reduction in BW load has been observed to influence vertical plantar in-shoe pressure (Thomson et al., 2017) and tibiofemoral force (Patil et al., 2012) so that anti-gravity treadmill might enable a progressive adaptation of loading tolerance without exposure to higher speed running. However, the previously cited literature has only quantified force in the vertical plane, a limitation of in-shoe pressure systems and negating the multi-planar mechanism of injury mechanism. Thomson et al. (2018) reported asymmetry in vertical force during running in ACL reconstructed athletes. Given the mechanistic association of knee valgus with ACL injury, for example, a multi-planar consideration of force during anti-gravity running during rehabilitation is warranted.

Tri-axial accelerometry offers a relatively high frequency means of collecting in-vivo loading data during running. Recent reviews have concluded that inertial measurement units located at the foot, tibia and lumbar spine were able to derive valid and reliable running gait data (Horsley et al., 2021; Zeng et al., 2022). Tri-axial accelerometers have also been used to quantify a PlayerLoad metric used commonly in elite team sports such as soccer and used as a predictor of injury (Barrett et al., 2016). When embedded within a GPS system the unit is typically located at the cervico-thoracic junction to enhance satellite reception and subsequent performance metrics such as distance covered, and speed derivatives. However, the location of the accelerometer has been shown to influence the magnitude of axial PlayerLoad during rehabilitative drills. Greig et al. (2019) reported significantly greater PlayerLoad at the tibia than at the cervico-thoracic junction in the vertical, medio-lateral and antero-posterior planes when performing a battery of ankle rehabilitation drills. Axial accelerometry and derived PlayerLoad metrics have also been shown to be sensitive to previous injury in a study of hopping tasks performed by elite soccer players (Mitchell and Greig, 2022).

The aim of the present study is to quantify the vertical, antero-posterior and medio-lateral mechanical loading response to running at different %BW in an elite male soccer player during ACL rehabilitation. Mechanical loading will be quantified using tri-axial accelerometers located at the cervico-thoracic junction, and mid-tibia of the operated and non-operated limb.

Methods

Participant

The case was a 26-year-old male professional soccer player, typically employed as an attacking midfielder or forward, with >300 appearances, and with no previous history of injuries. The player suffered an ACL rupture to his right (dominant) knee during match-play with surgical intervention to harvest a four-strand autologous hamstring semitendinosus and gracilis graft from the contralateral limb. Eight months into the rehabilitation pathway the player reported pain in the medial aspect of the same knee and underwent a medial meniscectomy. The subsequent rehabilitation was conducted by medical staff from the professional club, and written consent was provided by the player in accordance with the Helsinki Declaration.

Rehabilitation Program

At 4 weeks post-surgery the player had completed a battery of strength and physical capacity tests including knee flexor and extensor isokinetic dynamometry trials to the desired ≥90% limb symmetry index. The player had completed water- and subsequent land-based sessions focussing on running mechanics, with no evidence of bilateral asymmetry or observable limp. The player had also been exposed to progressive loading having performed plyometric drills including a hop test battery, with no evidence of movement compensations in the injured or contra-lateral limb. Based on successful progression through the objective rehabilitative markers at this stage, the player was deemed ready to begin running on an anti-gravity treadmill (Alter-G, Fremont, CA, USA). At 4-weeks post-surgery the player completed 2-minute running intervals at 10.2 km/hr with linear progression from 70% to 95% bodyweight at 5% increments. Linear progression rather than a randomised allocation of speed was used to reflect the rehabilitation context of the player. This running speed was equivalent to 30% of the player's maximum running speed determined from match-play and had been achieved during grass-based rehabilitation sessions in the preceding week. This is slower than the arbitrarily selected 60% of pre-injury maximal speed used by Taberner et al. (2020) used at 5.5 months post-surgery, but consistent with our rehabilitation pathway, the stage of rehabilitation, and the running speed achieved on the field.

Data Collection

Before entering the anti-gravity treadmill, the player was fitted with a tri-axial accelerometer (Catapult S5, Catapult Sports, Melbourne, Australia) situated at the superior musculotendinous junction of the Achilles tendon on both limbs and secured with zinc-oxide tape applied horizontally around the limb by the club physiotherapist. A third unit was placed at the cervico-thoracic junction and housed within a neoprene vest, worn routinely during the rehabilitation pathway. Orientation of each accelerometer was consistent with that typically adopted at the cervico-thoracic junction so that axial planes were defined consistently with previous literature (Greig et al., 2019). Planar acceleration was collected at a sampling frequency of 100Hz.

For each body weight percentage (%BW) a series of 10 consecutive strides (20 consecutive steps) was analysed, selected from the mid-stage of each 2-minute interval. For the cervico-thoracic (C7) accelerometer the alternate foot contacts were identified as being right (affected) or left (non-affected) foot contacts. For the right lower leg (LL) accelerometer only the right foot contacts were analysed, and similarly for the left lower leg. Four groups were therefore stratified, differentiating C7and LL, and the affected (AFF) and non-affected (NON) limb, thereby defining $C7_{AFF}$, $C7_{NON}$, LL_{AFF}, LL_{NON}. For each group, and at 70, 75, 80, 85, 90, and 95%BW, analysis was applied to each of the 10 foot contacts. Accelerometer location and %BW were defined as the independent variables.

Data Reduction and Statistical Analysis

For each foot contact, the instance of touchdown was defined by the peak instantaneous vertical acceleration. The magnitude of the vertical, medio-lateral and antero-posterior acceleration were recorded at touchdown. From the instant of touchdown and for the duration of foot contact, uni-axial PlayerLoad was calculated based on the rate of change of acceleration, as described by Greig et al. (2019). The accumulated PlayerLoad during each foot contact for the LL accelerometers was calculated in each plane.

Univariate general linear modelling was used to investigate a main effect for %BW and accelerometer location in each dependent variable. Where appropriate post-hoc analyses were applied to determine the directional main effect, with 95% confidence intervals for difference (CI*diff*) reported. Statistical significance was predetermined at $P \leq 0.05$, with main effects quantified using the F-statistic and supported by eta squared as a measure of effect size (ES), and interpreted as small ≤ 0.01; medium ≤ 0.06 and large ≥ 0.14. All data are subsequently presented as mean ± standard deviation.

Results

Acceleration at impact

Figure 1 summarises the influence of %BW and accelerometer location on the vertical acceleration at touchdown. There was a significant main effect for %BW (F = 3.352; P = 0.007; ES = 0.119), with 85%BW eliciting significantly greater magnitude than 70 – 80%BW (CI*diff* = -0.47 to 1.33 m.s^{-2}), within which range there was no difference ($P \geq 0.486$). There was no further increase in magnitude across the 85 – 95%BW range ($P \geq 0.082$).

There was also a significant main effect for accelerometer location with C7 eliciting lower magnitude than the LL (F = 246.88; $P < 0.001$; ES = 0.857; CI*diff* = -7.05 to -5.80 m.s^{-2}), although there was no difference between the AFF or NON limbs at C7 (P = 0.537) or LL (P = 0.154). There was no %BW *x* location interaction (F = 0.678; P = 0.802; ES = 0.076).

** Insert Figure 1 near here **

Figure 2 summarises the changes in medio-lateral acceleration at touchdown, with a significant main effect for %BW characterised by a similar pattern of equivalence in magnitude from 70 – 80%BW ($P \geq 0.072$), but with 85%BW greater than 70% BW (P = 0.042; CI*diff* = -0.23 to 1.76 m.s^{-2}), and no substantive further increase from 85 – 90%BW ($P \geq 0.082$).

There was a significant main effect for accelerometer location (F = 27.925; $P < 0.001$; ES = 0.403) with medio-lateral acceleration in NON greater than AFF at C7 (P = 0.030; CI*diff* = 0.09 to 1.74 m.s^{-2}), and LL_{NON} elicited significantly greater magnitude than all other locations ($P < 0.001$; CI*diff* = 2.50 to 4.13 m.s^{-2}).

There was also a significant %BW *x* location interaction (F = 2.342; P = 0.005; ES = 0.221) with LL_{AFF} shifting from a negative value (indicative of eversion) at 70-75%BW to an increasingly positive (inversion) value as %BW increased.

** Insert Figure 2 near here **

Figure 3 summarises the influence of %BW and accelerometer location on the antero-posterior acceleration at touchdown. There was a significant main effect for %BW (F = 13.488; P < 0.001; ES = 0.352) with a progressive increase from 70% through 75% (P = 0.044; CI*diff* = 0.02 to 1.57 $m.s^{-2}$) to 80%BW (P = 0.005; CI*diff* = 1.14 to 2.69 $m.s^{-2}$). Thereafter there was little variation from 85 – 95%BW (P ≥ 0.079).

There was no significant main effect for location (F = 0.955; P = 0.416; ES = 0.023) but there was a %BW *x* location interaction (P < 0.001) with a shift from a negative value at 70% towards a positive value with increasing %BW observed only at LL.

** Insert Figure 3 near here **

PlayerLoad during foot contact

Figure 4 summarises the influence of limb and %BW on uni-axial PlayerLoad. In the vertical plane there was a significant main effect for %BW (F = 4.611; P = 0.001; ES = 0.271) with 70% lower (P ≤ 0.041) than 75 – 95%BW (CI*diff* = -0.20 to -0.07 a.u.), which were themselves not different (P ≥ 0.145). There was a significant main effect for location (F = 16.651; P < 0.001; ES = 0.212) with the AFF limb exposed to significantly (P < 0.001) greater loading CI*diff* = 0.04 to 0.11 a.u.), and with no %BW *x* location interaction (F = 0.812; P = 0.545; ES = 0.061).

There was a significant (F = 3.758; P = 0.005; ES = 0.233) main effect for %BW in medio-lateral PlayerLoad which increased at 95% relative to all other settings (P ≤ 0.041; CI*diff* = -0.01 to 0.13 a.u.). There was no main effect for limb (F = 3.135; P = 0.082; ES = 0.048) but a %BW *x* limb interaction (F = 2.897; P = 0.021; ES = 0.189) highlighted that the directional effect for %BW was only evident in the AFF limb.

There was no significant main effect for %BW in antero-posterior loading (F = 1.654; P = 0.159; ES = 0.118) but there was a main effect for limb (F = 22.115; P < 0.001; ES = 0.263) with AFF exposed to greater loading (CI*diff* = 0.04 to 0.11 a.u.). A significant %BW x limb interaction (F = 2.969; P = 0.018; ES = 0.193) revealed that the limb difference was not evident in the range 80-85%BW.

** Insert Figure 4 near here **

Discussion

The aim of the present study was to investigate the multi-planar loading response to a linear increase in %BW during anti-gravity running, conducted as part of the rehabilitation pathway of a professional male soccer player post knee surgery. The uni-axial acceleration at touchdown did not display a linear increase with the step progression in %BW, but there was evidence of an inflection point at 85% BW in vertical and medio-lateral acceleration, and at 80%BW in antero-posterior acceleration. Above 85%BW there was no progressive increase in loading, and thus 70%BW and 85%BW represent discrete rehabilitative progressions. In support of this finding, Saxena and Granot (2011) concluded that being able to run at 85%BW was sufficient to safely recommend running outside with full bodyweight for patients following Achilles tendon surgery.

Beyond 85%BW, rehabilitative progressions might instead focus on increasing running speed which will increase the magnitude of loading (Thomson et al., 2021) and provide greater functional relevance for return to play. Alternatively, the rehabilitative focus might progress to free-running at the same speed, enabling a transition to the directional change fundamental to the activity profile of soccer and the mechanism of ACL injury. Tenforde et al. (2012) presented a pelvic stress injury case where the athlete was progressed from 70% through to 95%BW before successful return to 10,000m athletic competition. In this case the duration was also progressed in line with the competitive race duration, but for a soccer player the reactive, intermittent and multi-directional nature of the activity profile demand a different progression.

When quantifying the loading response to running, previous research has tended to focus on vertical forces or loading (Patil et al., 2012; Thomson et al., 2017, 2021). In this case the vertical acceleration at touchdown during treadmill running was no different between the affected and non-affected limb, irrespective of %BW. However, the affected limb was exposed to significantly lower impact acceleration in the medio-lateral plane, with implications for the genu valgum often associated with ACL injury (Alentorn-Geli et al., 2009). This might be indicative of a reduced loading tolerance, or a perceived reduced capacity to load the injured knee. Furthermore, this medio-lateral gait asymmetry was sensitive to the %BW setting, suggesting that the player was making mechanical adjustments to his running gait as loading increased. This might be specific to the treadmill running task but supports previous research that has identified movement compensations in players who have suffered previous ACL injury (Jordan et al., 2015; Baumgart et al., 2017; Mitchell et al., 2022). The planar-specific response to gait symmetry during treadmill running highlights the importance of multi-planar analysis in rehabilitation, with the symmetry in vertical acceleration masking latent deficits in medio-lateral acceleration. The risk of injury to this player would be increased if they were to progress to faster and/or multi-directional running at this stage based on vertical plane symmetry alone.

Analysis of injury risk, or readiness to progress in rehabilitation should also expand analysis beyond the instance of touchdown, with peak ACL strain observed around 80ms after touchdown (Withrow et al., 2006; Shin et al., 2007). The rapid changes in acceleration during the stance phase of running can be considered using the PlayerLoad metric, with higher values reflecting a greater rate of change in planar acceleration. Whilst previous research has considered PlayerLoad accumulated across a soccer match for example (Barrett et al., 2016), Mitchell et al. (2022) recently showed that peak instantaneous PlayerLoad was sensitive to previous injury in soccer players. In the present case, the affected limb was exposed to greater vertical PlayerLoad despite no asymmetry in vertical acceleration at touchdown during treadmill running. The subsequent changes in acceleration might therefore be of greater mechanistic importance than the magnitude at touchdown. In the medio-lateral and anterio-posterior planes the asymmetry in the affected limb was exacerbated at the higher %BW setting. The rapid change in medial to lateral (for example) acceleration might be indicative of joint instability, given the linear nature of treadmill running. At this stage of the rehabilitation pathway the player had achieved the predetermined threshold of ≥ 90% limb symmetry in strength, but the isokinetic trials in knee flexion and extension are restricted to the sagittal plane and do not present the same multi-planar challenge. The affected limb was exposed to greater PlayerLoad than the non-affected limb in all planes during the treadmill running task. This suggests that the uni-axial PlayerLoad metric has value in the objective monitoring of rehabilitation.

The present study also considered the sensitivity of accelerometer location. As expected, the vertical acceleration at touchdown was greater at the lower leg than at C7, supporting previous observations (Greig et al., 2019) and with implications for accelerometer placement to monitor rehabilitation. In contrast, antero-posterior impact acceleration was not affected by accelerometer location, which might reflect the relatively slow running speed and a subsequently shorter stride requiring little forward displacement of the foot impact ahead of the centre of gravity. Step time was maintained between 0.38 – 0.40s as loading was increased from 70% - 95%BW, suggesting a consistent stride frequency and thus a consistent stride length given the constant velocity of the treadmill. Vincent et al. (2022) suggested that anti-gravity treadmills might induce kinematic changes to the running technique including cadence, vertical centre of gravity displacement, ground contact time and flight time. The lack of such observations in this player might reflect their level of habituation with the treadmill, the relatively low running speed, and the characteristically flat running gait of soccer players given their functional focus on agility.

In this case performance outcome was maintained, the player was able to complete the prescribed duration on the anti-gravity treadmill at each %BW setting. However, analysis of movement strategy identified asymmetry in medio-lateral acceleration at touchdown, and asymmetry in the rate of change of loading in all planes. In a rehabilitative context, priority should therefore be given to analysis of movement strategy rather than movement outcome. Care should be taken not to generalise these findings beyond this specific case, with the injury history, rehabilitative stage, and linear treadmill task all likely to influence the magnitude and pattern of mechanical loading. Previous research using anti-gravity treadmills has studied post-operative patients (e.g. Eastlack et al., 2005; Saxena & Granot, 2011) or runners (e.g. Hambly et al., 2017; Thomason et al., 2017), and the multi-directional activity profile habitual to this soccer player might influence running gait and subsequent loading pattern. Future research might consider the changes in loading strategy during the rehabilitative pathway, a speed-matched comparison with running on the grass, and the return to train and play criteria that might be established. Techniques such as statistical parametric mapping might also be employed to investigate temporal changes in loading throughout the stance phase.

Conclusion

This case considers the efficacy of anti-gravity treadmill running 4 weeks into a rehabilitation pathway for a professional male soccer player. There was no evidence of a progressive, linear increase in multi-planar impact acceleration as loading was increased from 70-95%BW. Rather, an inflection point at 85% BW suggests that 70% and 85%BW represent unique loading challenges, with practical implications for rehabilitation and exercise progression. The affected limb was not exposed to greater vertical impact acceleration but the medio-lateral acceleration at impact was lower in the affected limb, indicative of movement compensations and bilateral gait asymmetry. Practitioners should therefore adopt a tri-axial consideration of loading and consider placement of the accelerometer, as the lower leg was exposed to greater loading than the traditionally used C7. The sensitivity of loading metrics to this case suggests that tri-axial accelerometry can provide an efficacious and accessible means of performing in-vivo monitoring during rehabilitation, advocating an emphasis on movement strategy (e.g. axial loading) rather than task outcome (e.g. running speed).

Disclosure Statement

No conflicts of interest to report.

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Figures

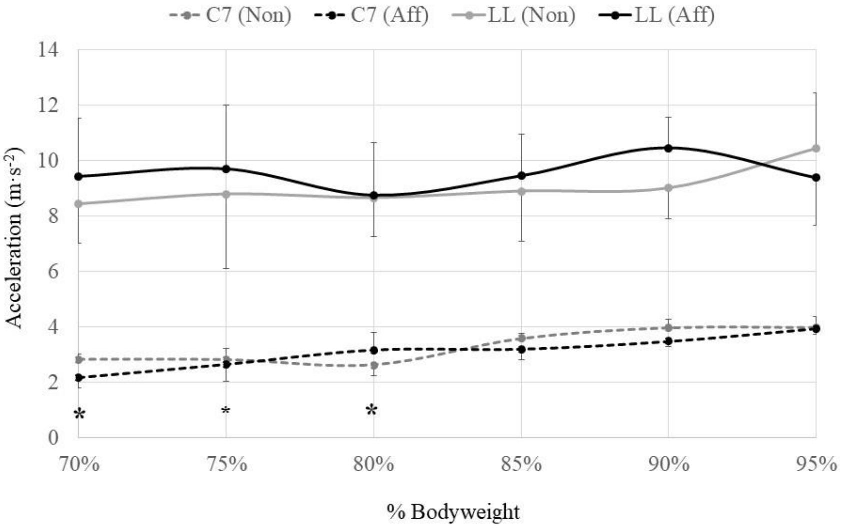

Figure 1. The influence of bodyweight support and accelerometer location on the vertical acceleration at touchdown. * denotes significantly different to 85%BW.

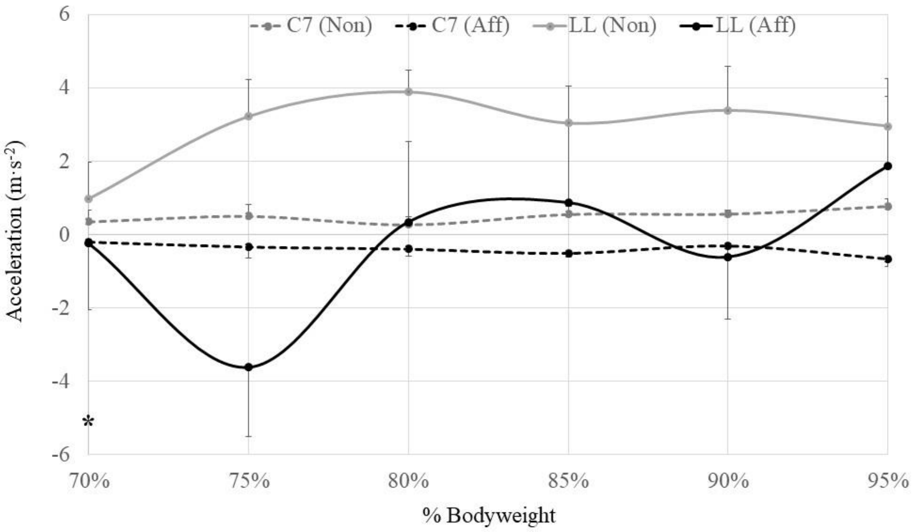

Figure 2. The influence of bodyweight support and accelerometer location on the medio-lateral acceleration at touchdown. * denotes significantly different to 85%BW.

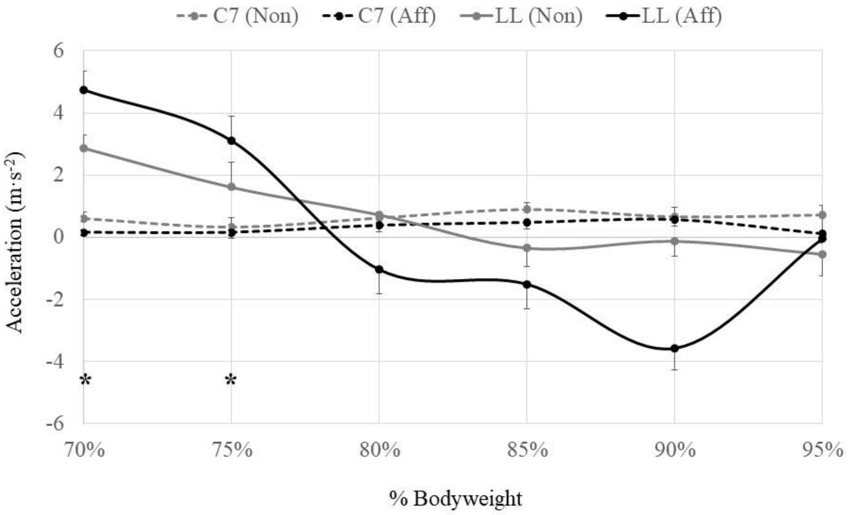

Figure 3. The influence of bodyweight support and accelerometer location on the antero-posterior acceleration at touchdown. * denotes significantly different to 80%BW.

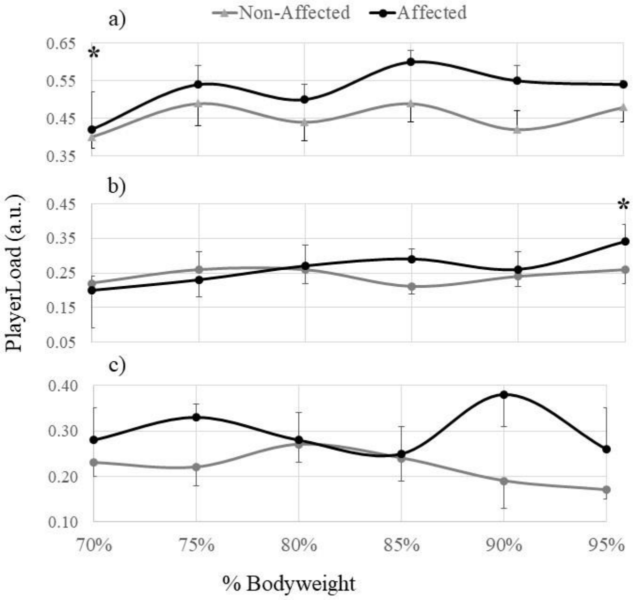

Figure 4. The influence of bodyweight support and injured limb on PlayerLoad during foot contact in the a) vertical, b) antero-posterior planes, and c) medio-lateral plane. * denotes significantly different to all other %BW.