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Review

The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review

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ABSTRACT

Background: Lower-limb stress fracture is one of the most common types of running injuries. There have been several studies focusing on the association between stress fractures and biomechanical factors. In the current study, the ground reaction force and loading rate are examined. There is disagreement in the literature about whether the history of stress fractures is associated with ground reaction forces (either higher or lower than control), or with loading rates.
Methods: A systematic review of the literature was conducted on the relationship between the history of tibial and/or metatarsal stress fracture and the magnitude of the ground reaction force and loading rate. Fixed-effect meta-analysis techniques were applied to determine whether or not the ground reaction force and/or loading rate are different between the stress fracture and control groups.
Findings: Thirteen articles were identified through a systematic search of the literature. About 54% of these articles reported significantly different vertical ground reaction force and/or loading rate between the stress fracture and control groups. Other studies (~46%) did not observe any significant difference between the two groups.
Meta-analysis results showed no significant differences between the ground reaction force of the lower-limb stress fracture and control groups ($P>0.05$). However, significant differences were observed for the average and instantaneous vertical loading rates ($P<0.05$).
Interpretation: The currently available data does not support the hypothesis that there is a significant difference between the ground reaction force of subjects experiencing lower-limb stress fracture and control groups. Instead, the vertical loading rate was found to be significantly different between the two groups.

1. Introduction

Lower-limb stress fractures are among the most common injuries to athletes and military recruits (Fredericson et al., 2006; James et al., 1978; Kowal, 1980; McBryde, 1985; Milner et al., 2006a). According to one report, up to 20% of all sports medicine clinical injuries are lower-limb stress fractures (Fredericson et al., 2006). Stress fractures are also a major problem for military recruits. According to Ross and Allsopp (Ross and Allsopp, 2002), stress fracture is the most common reason for the loss of training days for Royal Marine Recruits. These injuries cause so many lost training days due to the fact that stress fractures are among the more severe injuries of the lower-extremity musculoskeletal system, and need extended periods (4 to 8 weeks (Brukner et al., 1998)) of refraining from physically-demanding activities for recovery (Friedl et al., 1992; Jones et al., 1993; Macera et al., 1989; Rauh et al., 2006). Adding the time required for rehabilitative training to the recovery time results in a typical loss of 19 training weeks (Ross and Allsopp, 2002).

Stress fractures may happen in many different locations throughout the body (Fredericson et al., 2006), however they are relatively rare in the upper extremities (Fredericson et al., 2006). The most frequent types of lower-extremity stress fractures are tibial and metatarsal fractures. As Milner notes (Milner et al., 2006a), there are reports of the tibia being the most common fracture site accounting for 33–55% of the total number of stress fracture incidences (Brukner et al., 1996; Giladi et al., 1987; Matheson et al., 1987; Pester and Smith, 1992; Taunton et al., 1981). Queen *et al* reviewed the relevant literature (Queen et al., 2009) and concluded that metatarsal stress fractures account for up to 15.6% of all reported injuries.

A stress fracture can be defined as partial or complete fracture of bone as a result of repetitive sub-maximal loading. Stress fracture can therefore be compared with the fatigue fracture of engineering

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materials, although the mechanisms driving the two phenomena are somewhat different. Sub-maximal forces do not result in bone fracture, provided that there is enough time for reinforcement of the bone through remodeling. Instead, each loading cycle incrementally damages the bone, and these incremental damages accumulate cycle by cycle. If the loading frequency is low enough, there is sufficient time for osteoblasts to generate new bone and remove the damage. When the loading frequency is too high, the rate of bone resorption by osteoclasts exceeds the rate of bone generation and the bone weakens. Under certain conditions of continued repetitive loading of the weakened bone, fracture occurs.

Ground Reaction Force (GRF) is an important factor in the study of the kinetics of the lower-extremities during running. It has been used in a variety of experimental (Cavanagh and Lafortune, 1980; Gottschall and Kram, 2005) and numerical (Liu and Nigg, 2000; Zadpoor and Nikooyan, 2006, 2010) studies of running. The plot of the vertical GRF vs. time typically includes two force peaks (Fig. 1). Different names have been used for these two peaks: the 1st and 2nd peaks (Liu and Nigg, 2000; Zadpoor et al., 2007), vertical impact and vertical active force peaks (Bennell et al., 2004; Creaby and Dixon, 2008; Crossley et al., 1999; Dixon et al., 2006), and impact and propulsion peaks (Grimston et al., 1991; Wheat et al., 2003), respectively. The GRF is an approximate measure of the loading of the lower-extremity musculoskeletal system and is relatively easy to measure. The vertical loading rate (VLR) is defined as the slope of the initial part of the vertical GRF-time curve (between the foot strike and the vertical impact peak) (Munro et al., 1987). The VLR is an indication of how fast the vertical GRF rises to its 1st peak. In order to understand associations between loading and the history of stress fracture, several researchers have compared the characteristics of the GRF between control and stress fracture groups. There is disagreement between the results of these studies: while some studies conclude that there is no significant difference between the GRF of the stress fracture group and that of the control group, other researchers report a substantial difference.

The importance of understanding associations between the GRF and the history of stress fracture is three-fold. Firstly, understanding the association between loading and stress fracture allows for a better design of future studies and a potentially better understanding of the etiology of stress fracture, which is not currently well understood. Secondly, a significant correlation between the GRF and the history of stress fracture may present us with the opportunity of using the GRF as a relatively cheap diagnostic tool. Nevertheless, one should note

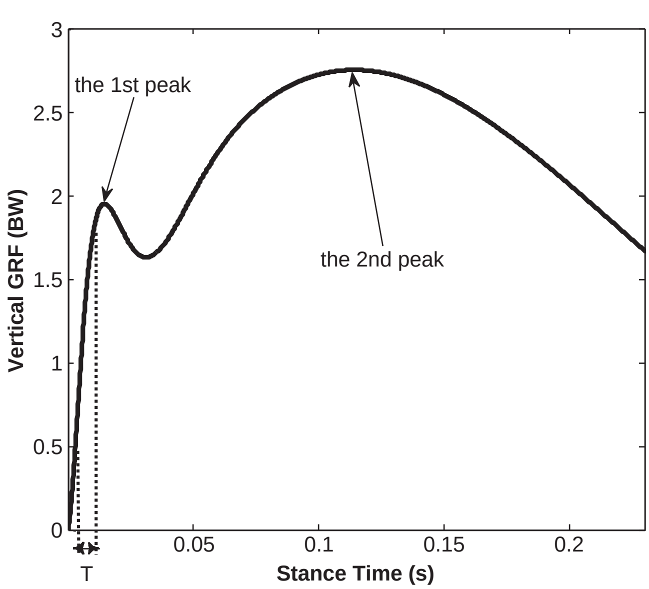

Fig. 1. Typical vertical GRF vs. stance time. T: the time period during which the VLR is calculated.

that the vast majority of currently available studies are retrospective. Therefore, their results cannot be used to assign causality and may be at most indicative of any such diagnostic opportunity. Finally and given that the GRF is dependent on the type of footwear (Clarke et al., 1983; Logan et al., 2010), any such correlation can be used to prevent stress fractures by designing appropriate footwear for runners and military recruits.

This paper presents a systematic review of the literature, aimed at understanding associations between the characteristics of the GRF and lower-limb (tibial/metatarsal) stress fractures. An exhaustive literature search is carried out and the relevant papers are identified and reviewed. Moreover, a meta-analysis is carried out to combine the results of the contradictory studies into a single larger-scale experiment that is more decisive, informative, and statistically relevant.

2. Methodology

2.1. Review method

PubMed online was used as the primary search database. The ISI Web of Science and Scopus were surveyed as complementary databases. The following search strategy (keywords) was used:

(stress frac*) AND (load* OR force* OR impact* OR impact force* OR ground reaction force*)

The search was performed in April 2010 and resulted in a total number of 503 articles and abstracts. The abstracts of the papers were screened by both authors to select articles for inclusion in the review. The inclusion criteria were as follows:

1. The vertical GRF characteristic of both stress fracture group and a control group were presented in the study.
2. The subjects in the stress fracture groups had experienced a tibial or metatarsal stress fracture.

All references in the included articles were also screened and the related articles were selected and reviewed. There was no exclusion based on the gender and the number of subjects. Three of the studies included in the meta-analysis (Davis et al., 2004; Ferber et al., 2002; Grimston et al., 1994) were published as abstracts. Therefore, they do not include enough methodological details to enable us to judge their quality. For full-length articles, the methods used for the measurement of the GRF were quite similar for each of the studies, therefore no additional study was excluded based on methodological deficiency. There was no disagreement between the authors in selection of the studies eligible for inclusion in the meta-analysis, and the exclusion criterion resulted in 13 selected articles (Table 1).

2.2. Meta-analysis

Meta-analysis has recently been used in many different areas of research (Borenstein et al., 2009; De Winter et al., submitted for publication) to combine various studies into a single study with a larger number of subjects and a greater statistical precision. In this paper, the fixed-effect meta-analysis (Borenstein et al., 2009) was used to calculate the mean weight of the size effects (M), the lower and upper limits of the summary effects (LL_m and UL_m), and the p-values among all included studies (Table 2). Separate sub-analyses were carried out for the papers that study tibial stress fracture and the ones that study metatarsal stress fracture. The detailed formulation and calculation process can be found in the electronic annex accompanying the paper.

The value of standard deviation (SD) in each study and each group (stress fracture and control groups) is required to calculate the corrected size effect. However, a few studies (Table 2) did not provide the

Table 1
The details of the stress fracture and control groups in the selected studies.

Author and publication year	Control group			Stress fracture group			
	No.	Sex	Age	No.	Sex	Age	Description of injury
Creaby and Dixon (2008)	20	Male	22.6 (3.8)	10	Male	20.3 (3.5)	Tibial stress fracture
Pohl et al. (2008)	30	Female	25.0 (9.0)	30	Female	28.0 (10.0)	Tibial stress fracture
Bennell et al. (2004)	22	Female	30.6 (6.9)	13	Female	29.4 (8.4)	Tibial stress fracture
Milner et al. (2006a)	20	Female	25.0 (9.0)	20	Female	26.0 (9.0)	Tibial stress fracture
Zifchock et al. (2006)	25	Female	24.4 (8.9)	24	Female	26.9 (9.2)	Tibial stress fracture
Davis et al. (2004)	5	Female	–	5	Female	–	Tibial stress fracture
Ferber et al. (2002)	10	Female	–	10	Female	–	Tibial stress fracture
Crossley et al. (1999)	23	Male	24.4 (6.2)	23	Male	25.1 (4.9)	Tibial stress fracture
Grimston et al. (1994)	5	–	–	5	–	–	Tibial stress fracture
Grimston et al. (1991)	8	Female	32.8 (0.7)	6	Female	26.9 (3.2)	Tibial/femoral-neck stress fracture
Bischof et al. (2010)	15	Female	22.1 (3.4)	9	Female	24.4 (6.2)	Metatarsal stress fracture
Queen et al. (2009)	15	Female	24.7 (5.2)	9	Female	22.2 (3.0)	Metatarsal stress fracture
Dixon et al. (2006)	10	–	23.0 (4.6)	10	–	20.9 (2.5)	Metatarsal stress fracture

values of standard deviation, so for these studies, the reported *p*-value (Table 2) was used to estimate the *SD*. For each group, the *SD* was calculated as follows:

$$SD_i = SE_i \cdot \sqrt{N_i} \tag{1}$$

$$SE_i = \frac{\overline{X}_i - mean(\overline{X}_1, \overline{X}_2)}{Z_i}, i = 1, 2 \tag{2}$$

where N_i and X_i are the number of subjects and the mean value of the experimental parameter (e.g. GRF) in each group, respectively. The *Z*-value was calculated from the *P*-value as follows:

$$|Z| = \Phi^{-1}\left(1 - \frac{p}{2}\right) \tag{3}$$

where Φ^{-1} is the inverse function of the standard normal cumulative distribution function (Φ).

For estimation of the *SD*, the *Z*-values of the two groups were assumed to be the same ($Z = Z_1 = Z_2$), resulting in the same value of *SD* for the stress fracture and control groups (the values are marked with asterisk in Table 2). The values of the standard deviation calculated using the *t*-test were found to be similar to the values calculated using *Z*-test.

3. Results

3.1. Systematic review

In the studies summarized in Table 2, the GRF was measured using a force plate placed in the center of a running path. Different types of force plates (AMTI, Kistler, Bertec Corporation, etc) were used. The sampling frequency, the length of the runway path, and the running velocity varied in the different studies in the range of 500–1200 Hz, 10–40 m, and 3.3–4.0 m/s $\pm$10%, respectively. Different numbers of running trials, varying from 2 to 10 for each foot, were used in these studies. Most studies used the average of all measured trials for each subject (Davis et al., 2004; Milner et al., 2006a; Queen et al., 2009; Zifchock et al., 2006).

Although there was no unique definition for the time period during which the VRF was calculated (i.e. T, see Fig. 1), most studies used the time period within which the force-time curve is most linear (Milner et al., 2006a; Munro et al., 1987). Some studies defined and used the average (AVLR) and instantaneous (IVLR) vertical loading rates (Davis et al., 2004; Ferber et al., 2002; Milner et al., 2006a; Zifchock et al., 2006). In those studies, the AVLR was defined as the change in the GRF divided by the time-period (T), while the IVLR was considered as the maximum of the VLRs calculated at different time samples in the whole time-period (T).

Most of the selected papers studied female runners rather than male runners (Table 1). In almost all selected studies (Table 1), participants in both stress fracture and control groups were chosen from young adults (mean age: 25.09 $\pm$ 5.48).

Out of the 13 selected papers (Table 1), 10 papers (~77%) study tibial stress fracture and 3 papers (~23%) study metatarsal stress fracture.

A summary of the self-stated conclusions is presented in Table 3 and shows that the studies do not agree on whether or not the vertical GRF and/or loading rate are significantly different between the stress fracture and control groups. Some studies (~54%) reported significantly higher/lower vertical GRF or vertical loading rate for the stress fracture group as compared to the control group, while some others (~46%) did not observe any significant difference between the two groups (Table 3).

In addition to the vertical GRF and the vertical loading rate, which have received much attention, some of the studies measured and compared other parameters between the stress fracture and control groups. The horizontal braking force in the stress fracture group was reported in a few studies to be significantly higher (Grimston et al., 1991; Zifchock et al., 2006) or lower (Grimston et al., 1994) than that of the control group, but in other studies it was found to be not significantly different between the groups (Bennell et al., 2004; Bischof et al., 2010; Crossley et al., 1999; Dixon et al., 2006). A few studies also compared the free moment of the GRF (the torque between the ground and foot) between the stress fracture and control groups. The magnitude of the free moment was not different between the two groups in some studies (Creaby and Dixon, 2008) while it was reported to be higher in the stress fracture group in some other studies (Milner et al., 2006b; Pohl et al., 2008).

Dixon *et al* (Dixon et al., 2006) also compared the GRF variables between the stress fracture and control groups in barefoot running. The results were similar to those of the shod-runners: there was no significant difference between the stress fracture and control groups in terms of the peak GRF, peak loading rate, or the horizontal braking force.

The potential effect of the muscle fatigue on the GRF variables in the distance running was also studied (Grimston et al., 1994). The results of the study showed that for the subjects in the stress fracture group, the vertical and anterior force peaks were significantly higher towards the end of a 45 minutes exercise.

3.2. Meta-analysis

The results of the fixed-effect meta-analysis of all included studies (Table 4) show that there is no significant difference between the

Table 2
The first and the second vertical GRF peaks, the average (AVLR) and instantaneous (IVLR) vertical loading rates, and the *P*-value between the stress fracture and control groups for the selected studies.

Author and publication year	Control group				Stress fracture group				*p*-value			
	GRF 1st peak (BW)	GRF 2nd peak (BW)	AVLR (BW/s)	IVLR (BW/s)	GRF 1st peak (BW)	GRF 2nd peak (BW)	AVLR (BW/s)	IVLR (BW/s)	GRF 1st peak (BW)	GRF 2nd peak (BW)	AVLR (BW/s)	IVLR (BW/s)
Creaby and Dixon (2008)	1.81 (0.26)	2.67 (0.21)	–	–	1.91 (0.22)	2.49 (0.18)	–	–	0.164[a]	–	–	–
Pohl et al. (2008)	–	–	66.0 (22.4)	83.8 (23.2)	–	–	74.2 (23.5)	88.2 (24.7)				
Bennell et al. (2004)	2.080 (0.38)	2.79 (0.25)	–	–	1.94 (0.30)	2.75 (0.22)	–	–	0.320[b]	0.470[b]	–	–
Milner et al. (2006a)	1.70 (0.32)	–	66.31 (19.52)	79.65 (18.81)	1.84 (0.21)	–	78.97 (24.96)	92.56 (24.7)	0.057[a]	–	0.041[a]	0.036[a]
Zifchock et al. (2006)	1.811 (0.45)	2.51 (0.19)	72.97 (27.93)	87.61 (25.90)	1.91 (0.29)	2.49 (0.17)	82.43 (29.28)	95.49 (27.03)				
Davis et al., (2004)	–	2.63 (0.07)[c]	62.91 (15.03)[c]	81.03 (17.33)[c]	–	2.55 (0.07)[c]	88.20 (15.03)[c]	112.88 (17.33)[c]	–	0.150[d]	0.060[d]	0.040[d]
Ferber et al. (2002)	–	2.48 (0.85)[c]	77.52 (29.44)[c]	108.89 (41.82)[c]	–	3.87 (0.85)[c]	117.93 (29.44)[c]	158.61 (41.82)[c]	–	0.010[d]	0.030[d]	0.030[d]
Crossley et al. (1999)	1.97 (0.34)	2.86 (0.19)	–	–	1.89 (0.39)	2.84 (0.24)	–	–	–	–	–	–
Grimston et al. (1994)	2.24 (0.27)[e]	2.68 (0.09)[e]	–	–	1.84 (0.13)[e]	2.48 (0.09)[e]	–	–	–	–	–	–
Grimston et al. (1991)	1.85 (0.14)[e]	2.51 (0.11)[e]	–	–	2.09 (0.22)[e]	2.68 (0.07)[e]	–	–	–	–	–	–
Bischof et al. (2010)	–	2.40 (0.19)	–	–	–	2.51 (0.09)	–	–	–	–	–	–
Queen et al. (2009)	1.64 (0.44)	–	–	–	1.49 (0.36)	–	–	–	–	–	–	–
Dixon et al. (2006)	1.88 (0.30)	2.72 (0.22)	–	178.00 (49.00)	1.93 (0.43)	2.69 (0.33)	–	156.0 (54.0)	0.380[b]	0.400[b]	–	0.190[b]

[a] 1-tailed *p*-value.
[b] 2-tailed *p*-value.
[c] The standard deviation (*SD*) was not given in the original article and was therefore estimated.
[d] The direction(s) of *p*-value was not stated and was assumed to be 2-tailed.
[e] The standard error (*SE*) was given in the original article and the *SD* values were calculated using the *SE* values.

vertical GRF peaks of the stress fracture group and those of the control group ($P>0.05$, Table 4). However, the AVLR and IVLR are significantly higher for the stress fracture group ($P<0.05$, Table 4). The same conclusion holds when the meta-analysis is performed only within the tibial or metatarsal stress fracture groups, except in the case of the IVLR of the metatarsal fracture group for which only one study is included (Table 4).

4. Discussion

The studies reporting on associations between the GRF and lower-limb stress fracture were reviewed and their results were analyzed using fixed-effect meta-analysis. It was found that the magnitude of the GRF is not significantly different between the stress fracture and control groups. However, the vertical loading rate was significantly different between the two groups.

4.1. Results of the meta-analysis

One normally expects the subjects who experience more severe loading to be significantly more likely to have experienced stress fracture, however the results of the meta-analysis show otherwise. In explaining the results of the meta-analysis, one should note that in a group of people performing the same task, the ones who develop stress fracture should either have experienced more severe loading or have been more vulnerable to loading (or possibly a combination of both). For example, several studies have shown that athletes and military recruits who develop stress fracture (prospective studies) (Beck et al., 1996, 2000; Milgrom et al., 1988) or have a history of stress fracture (retrospective studies) (Crossley et al., 1999) exhibit a tendency of having bones with smaller cross sectional area. The above-mentioned studies investigated the bone's resistance to fracture as a risk factor, conversely, the hypothesis behind most of the studies surveyed here (Table 1) is that stress fractures develop due to more severe loading of the bones. One should note that the loading of bones consists of two parts: external loading and internal loading. The GRF can be assumed to represent external loading, however muscles, tendons, and ligaments also contribute to the internal forces that bones experience. Moreover, the impact attenuation mechanism also plays a role in the amount of load transferred to bones. Therefore, the characteristics of the GRF can at best describe the external loading of bones, meaning that the GRF may at most be one of the risk factors involved. The reason why GRF has received so much attention as a risk factor for stress fractures is its ease of measurement. As opposed to full kinematics measurements that require significant time and resources, GRF can be readily measured for a relatively large number of subjects. In summary, the counterintuitive result that the magnitude of the GRF is not significantly different between the stress fracture and control groups may be due to the differences that exist in the geometry and/or strength of bones of different individuals, or that the GRF cannot fully represent the loading of bones.

As previously mentioned, the meta-analysis indicates that the loading rate is significantly different between the stress fracture and control groups. This conclusion is consistent with the results of the mechanical tests performed on bone samples. Stress fracture is also phrased as "fatigue fracture" in the literature (Carter and Hayes, 1977). That is because the conditions experienced by bone during mechanical fatigue tests are comparable with the ones experienced by bone during the time period preceding stress fracture. In mechanical fatigue testing of bone samples, it has been found the fatigue strength of bone is significantly less when the load is applied at a higher strain rate (Schaffler et al., 1989). Given this observation about bone samples, it is not surprising that the loading rate is found to be significantly higher in the stress fracture group.

Table 3
The self-stated conclusions in the selected studies on the differences in the ground reaction force variables (VGRF peaks, AVLR, IVLR) between the control and stress fracture (SF) groups.

Author and publication year	Self-stated conclusion	
	Comparing the vertical GRF between the control and stress fracture groups	Comparing the VLR between the control and stress fracture groups
Creaby and Dixon (2008)	No significant difference was found	–
Pohl et al. (2008)	–	No significant difference was found
Bennell et al. (2004)	No significant difference was found	No significant difference was found
Milner et al. (2006a)	The SF group showed nonsignificant higher GRF	The SF group showed higher VLR
Zifchock et al. (2006)	–	The SF group showed higher VLR
Davis et al. (2004)	–	The SF group showed higher VLR
Ferber et al. (2002)	The SF group showed significantly higher GRF	The SF group showed significantly higher VLR
Crossley et al. (1999)	No significant difference was found	No significant difference was found
Grimston et al. (1994)	The SF group showed significantly lower GRF	–
Grimston et al. (1991)	The SF group showed significantly higher GRF	–
Bischof et al. (2010)	No significant difference was found	–
Queen et al. (2009)	The SF group showed lower GRF	–
Dixon et al. (2006)	No significant difference was found	No significant difference was found

4.2. Limitation of the surveyed studies

In addition to the results of the meta-analysis, it is also important to discuss the limitations of the studies surveyed in this review. The first limitation is the retrospective nature of most of the studies targeted towards identifying risk factors. The individuals with a history of stress fracture may have afterwards developed a running pattern that results in relatively smaller GRF values. This may not be a serious limitation, because it has been consistently shown that individuals with a history of stress fracture are more prone to subsequent fractures (Macera et al., 1989; Walter et al., 1989), meaning that the adaptations that follow stress fractures may not be important in reducing risk factors. Moreover, Creaby and Dixon (Creaby and Dixon, 2008) cite a study involving an animal model (Seebeck et al., 2005) in which it is shown that the characteristics of the GRF return to their pre-fracture conditions after the fracture healed.

The second limitation of most studies is that their experiments are conducted using a fixed running speed for all subjects. Every individual has a different running style. As Queen *et al* note (Queen et al., 2009), it has been shown by several researchers (Clarke et al., 1983; Jorgensen, 1990; Soutaslittle et al., 1987; Stergiou et al., 1999) that the kinematics of running is significantly different when running at different speeds. Therefore, asking the subjects to run at the same speed may have altered their preferred normal running style. An alternative would be to allow subjects run at their own preferred speed and co-vary for speed (Queen et al., 2009).

The third limitation is that the experiments are normally conducted for a short period of time. This method of experimentation neglects the effects that are important only when running for longer periods of time, a prominent example being muscle fatigue. Muscle activity is proposed to play an important role in regulating the GRF during running (Zadpoor and Nikooyan, 2010). When muscles fatigue, the amount of energy transmitted to the surrounding bones increases (Fredericson et al., 2006). Grimston *et al* (Grimston et al., 1994) observed that towards the end of a 45 min running experiment, the GRF increases more for individuals who have had a history of stress fracture than for the control group. Stress fracture may therefore be more likely to happen in individuals whose muscles fatigue more rapidly (Bennell et al., 2004) or the ones whose muscles fatigue at different rates, resulting in imbalance on the shank (Mizrahi et al., 2000). Therefore, one needs to evaluate the GRF in long running exercises in order to be able to reliably assess the differences between the GRF of the stress fracture and control groups.

Finally, most studies have only considered vertical GRF. The horizontal component of the GRF may be important in stress fractures as well (Dixon et al., 2006). For example, the force bearing capacity of the third metatarsal is shown to be less in the horizontal direction compared to the vertical direction (Arangio et al., 1998). As a result, measurement of all components of the external forces is required, particularly for the risk analysis of metatarsal stress fractures.

Table 4
The results of the meta-analysis for all studies, the studies in the tibial stress fracture, and metatarsal stress fracture groups.

Selected studies	Value	GRF 1st peak (BW)	GRF 2nd peak (BW)	AVLR (BW/s)	IVLR (BW/s)
All studies	M	0.017	−0.023	0.546	0.371
	LL_m	−0.222	−0.272	0.251	0.094
	UL_m	0.257	0.226	0.840	0.648
	p	0.887	0.857	0.000	0.009
Only tibial stress fracture	M	0.105	−0.092	0.546	0.464
	LL_m	−0.159	−0.367	0.251	0.171
	UL_m	0.369	0.182	0.840	0.757
	p	0.437	0.511	0.000	0.002
Only metatarsal stress fracture	M	−0.120	0.294	–	−0.409
	LL_m	−0.701	−0.293	–	−1.258
	UL_m	0.461	0.881	–	0.440
	p	0.685	0.327	–	0.173

4.3. Limitations of the meta-analysis

One of the limitations of the reported meta-analysis is that studies conducted on athletes and military recruits were aggregated due to lack of sufficient data to conduct separate meta-analyses for each of those groups. We, however, note that the mechanisms governing stress fractures may be different between athletes and military recruits (Creaby and Dixon, 2008).

The results of the meta-analysis for loading rate are consistent with real data from bone samples, suggesting that a more rapid application of force (strain rate) should result in a more severe damage to bone (Schaffler et al., 1989). However, the number of studies reporting the loading rate is less than the number of studies reporting the GRF. Therefore, one has to be careful in interpreting the results of the meta-analysis conducted for the loading rate.

4.4. Recommendation for future research

Having systemically reviewed the relevant literature on associations between the characteristics of the GRF and lower-limb stress fractures, we are ready to recommend on the specifications of ideal future studies in this area. More prospective studies with larger number of participants are required. The experiments should include both short distance and long distance running exercises. An integrated modeling-experiment approach may be required to understand why the magnitude of the GRF is not related to the history of stress fracture. However, this will be a costly approach as the geometry and density of the bones as well as the full kinematics of running need to be recorded.

5. Conclusions

The meta-analysis showed that the currently available data does not support the hypothesis that there is a significant difference between the GRF of the stress fracture group and that of the control groups. However, the loading rate was found to be significantly different between the two groups. Analysis of the limitations of the current studies showed that more prospective studies with larger numbers of participants and better designs are needed to enable more decisive conclusions in the future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.clinbiomech.2010.08.005.

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