Tibial Stress Changes in New Combat Recruits for Special Forces: Patterns and Timing at MR Imaging[1]

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Purpose: To characterize the incidence, location, grade, and patterns of magnetic resonance (MR) imaging findings in the tibia in asymptomatic recruits before and after 4-month basic training and to investigate whether MR imaging parameters correlated with pretraining activity levels or with future symptomatic injury.

Materials and Methods: This study was approved by three institutional review boards and was conducted in compliance with HIPAA requirements. Volunteers were included in the study after they signed informed consent forms. MR imaging of the tibia of 55 men entering the Israeli Special Forces was performed on recruitment day and after basic training. Ten recruits who did not perform vigorous self-training prior to and during service served as control subjects. MR imaging studies in all recruits were evaluated for presence, type, length, and location of bone stress changes in the tibia. Anthropometric measurements and activity history data were collected. Relationships between bone stress changes, physical activity, and clinical findings and between lesion size and progression were analyzed.

Results: Bone stress changes were seen in 35 of 55 recruits (in 26 recruits at time 0 and in nine recruits after basic training). Most bone stress changes consisted of endosteal marrow edema. Approximately 50% of bone stress changes occurred between the middle and distal thirds of the tibia. Lesion size at time 0 had significant correlation with progression. All endosteal findings smaller than 100 mm resolved or did not change, while most findings larger than 100 mm progressed. Of 10 control subjects, one had bone stress changes at time 0, and one had bone stress changes at 4 months.

Conclusion: Most tibial bone stress changes occurred before basic training, were usually endosteal, occurred between the middle and distal thirds of the tibia, were smaller than 100 mm, and did not progress. These findings are presumed to represent normal bone remodeling.

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Bone stress injuries, more specifically stress fractures, are the most common and potentially serious overuse injuries (1). They are seen in up to 30% of military recruits, are related to intensive training programs, and are thus most common in those training for elite forces (1). Most military-related stress injuries are located in the tibia (2–4). These overuse injuries are associated with pain symptoms that require rest, thus resulting in loss of training days (5); however, they can also be asymptomatic (6–8).

Risk factors for stress injuries include lower bone biomechanical strength (3,9), muscle weakness, caloric restriction, lower bone density, leg length, race, tobacco and alcohol use, and a sedentary lifestyle before training (10,11). Although most study results indicate that a greater level of preinduction activity results in a lower risk of developing stress injuries (12–14), this is not universally accepted (15,16).

In recent years, magnetic resonance (MR) imaging has been considered the most sensitive and specific imaging modality for the diagnosis of early stress injuries (17,18). However, it is believed that MR imaging may be too sensitive and may result in overdiagnosis, especially in asymptomatic patients. Bergman et al (6) and Lazzarini et al (19) reported that bone marrow edema–like signal can be seen in the feet and ankles at MR imaging in asymptomatic runners and ballet dancers. Schweitzer and White (20) showed that remodeling is an edematous process. Gefen et al (21), Shabshin et al (22), and Shabshin and Schweitzer (23) also suggested that bone marrow–like signal in children can represent normal bone remodeling. Bone stress injuries are categorized at MR imaging into stress fractures and stress response or reaction with somewhat different imaging appearances (8).

Special Forces training programs are associated with both extremely demanding physical requirements and highly motivated recruits, who might downplay their symptoms (24). Owing to its high sensitivity and specificity, MR imaging could be used to obtain an objective status of suspected stress injuries both before and through the course of training. However, it is unclear whether bone stress changes at MR imaging reflect or predict clinically important stress injuries.

The purpose of this study was to characterize the incidence, location, grade, and patterns of MR imaging findings in the tibia in a group of asymptomatic elite military recruits before and after completion of a 4-month training period and to investigate whether MR imaging parameters correlated with pretraining activity levels or with the future development of symptomatic bone stress injury.

Advances in Knowledge

- More than 60% of asymptomatic new recruits for Special Forces had stress changes in the tibia at MR imaging on induction day.
- In most asymptomatic recruits undergoing vigorous physical activity, stress changes of the bones had no clinical importance and did not progress; however, endosteal lesions larger than 100 mm can progress and thus may reflect abnormal stress and deserve close clinical follow-up.

Materials and Methods

Subjects

Fifty-five young men (mean age, 18.6 years; range, 17–21 years) entering Israeli Special Forces basic training volunteered to participate in this study. All volunteers were medically cleared by a physician prior to entering the training program and were eligible to participate in the study only after they signed a written informed consent form. This study was approved by two institutional review boards (of the Sheba Medical Center [the medical center where the MR imaging studies were performed] and the Israel Defense Forces) and by the Committee for Research and Human Subjects of the U.S. Army Research Institute of Environmental Medicine. This study was compliant with the Health Insurance Portability and Accountability Act.

Implication for Patient Care

- Asymptomatic bone marrow edema related to vigorous physical activity in military recruits may not require modification of training or other treatment.

Activity History Assessment

The recruits completed a physical activity questionnaire before training initiation that included questions on the type, frequency, and period of time they were involved in the activity. Outcome measures were aerobic endurance period of training during the year prior to basic training (in months), number of practices weekly, and the duration of each practice (in minutes).

Anthropometry and Aerobic Capacity Assessment

The following measurements were performed: Height (in centimeters) was measured by using a stadiometer, and weight (in kilograms) was measured by using a metric scale (±10 g). Tibial length was measured by means of palpation as the distance from the distal aspect of the medial malleolus to the proximal medial joint line. Maximal aerobic capacity (as maximum oxygen consumption [Vo_2max]) was measured

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Abbreviations:
STIR = short inversion time inversion recovery
Vo_2max = maximum oxygen consumption

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Guarantors of integrity of entire study, A.H., D.S.M., N.S.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; agrees to ensure any questions related to the work are appropriately resolved, all authors; literature research, A.H., D.S.M., R.K.E., N.S.; clinical studies, A.H., D.S.M., R.K.E., Y.F., N.S.; statistical analysis, A.H., D.S.M., Y.F., M.E.S.; and manuscript editing, all authors

Conflicts of interest are listed at the end of this article.

on a treadmill connected to a metabolic cart (Sensormedics, San Diego, Calif).

MR Imaging

The subjects' tibiae were imaged with MR imaging on the day of recruitment (time 0) and after 4 months of basic training (time 4). At each time point, the subjects underwent imaging of the tibia as follows: Vitamin E markers were adhered to the skin on the interface between the proximal and middle thirds and between the middle and distal thirds of the calf (approximately at 33% and 66% of tibial length). Both tibiae were imaged with a 0.5-T MR imaging unit (Signa SP; GE Medical Systems, Milwaukee, Wis) or a 3.0-T MR imaging unit (Signa HDxt; GE Medical Systems) and a flex coil, with subjects in the supine position. Sequences included coronal and axial short inversion time inversion-recovery (STIR) sequences (repetition time msec/echo time msec, 2400–6300/42–57; inversion time msec, 130–180) and coronal gradient-echo in- and out-of-phase sequences (repetition time, 90–185 msec; flip angle, 90°; out-of-phase and in-phase echo times at 3.0 T, 2.4 and 4.7–4.8 msec, respectively; out-of-phase and in-phase echo times at 0.5 T, 7.1 and 14.2 msec, respectively). The section thickness was 4–5 mm, and the field of view was 250–350 mm. The in-phase images were T1-weighted and could potentially demonstrate fracture lines. The combination of in- and out-of-phase images could aid in problem solving with incidental findings.

The MR images were independently evaluated by two musculoskeletal radiologists (N.S. and M.E.S., with 7 and 20 years of experience, respectively) who were blinded to clinical symptoms, level of physical activity, physical examination results, anthropometry findings, and aerobic capacity. If there was a disagreement, the evaluation was reached in consensus.

The MR images were evaluated for the grade of stress reaction according to the grading system of Fredericson et al (8) as follows: Periosteal edema or reaction only was given a grade of I; bone marrow edema on T2-weighted fat-suppressed images, a grade of II; high signal intensity in the marrow on T2-weighted fat-suppressed images and low signal intensity in the marrow on gradient-echo T1-weighted images, a grade of III; and a fracture line, a grade of IV. Bone marrow edema patterns were classified as endosteal (linear continuous high signal intensity along the endosteum) or patchy (cloudlike and amorphous with indistinct margins). Lesion length was measured for endosteal marrow edema. Because areas of patchy marrow edema demonstrated indistinct margins and discontinuity, their length was not measured. Location of the findings within the tibia was assigned to proximal, middle, and distal thirds. When findings were bilateral, they were analyzed for symmetry of pattern, measurements, and location.

For evaluation of the natural course of bone stress change development, the MR imaging results were not reported to the orthopedic surgeons or to commanders. Thus, physical activity was not modified on the basis of the MR imaging results, even if they were positive. Modification of activity was based on clinical symptoms only and according to the Israel Defense Forces protocol (25).

Biweekly Physician Follow-up

As part of the study, recruits underwent a targeted physical examination performed by two orthopedic surgeons who had specific subspecialty experience in stress fractures (25) and who were blinded to the MR imaging results. Diagnosis of clinically suspected stress fractures was confirmed with radiography (cortical thickening, presence of fracture line) or scintigraphy (dimension, extension, and concentration of tracer yielding a stress fracture grade of I–IV), as part of the recruits' medical care, unrelated to their study involvement (25,26).

Control Group

A group of 10 recruits who did not perform vigorous self-training prior to recruitment or during their non–physically demanding basic training program comprised the control group and underwent the same protocol as the study group.

Statistical Analysis

For each time point, 0 and 4 months, subjects were classified into two groups: those with tibia bone stress changes at MR imaging (eg, periosteal reaction, endosteal or patchy bone marrow edema) and those with negative MR imaging findings (healthy subjects). For all outcome measures, data were presented as means ± standard deviation. Because the data distribution was not normal, a nonparametric Mann-Whitney test was used to detect differences between the groups. The χ^2 test was used to detect differences in clinical stress injury occurrence between subjects with and those without bone stress changes. The Spearman nonparametric correlation test was used to detect correlation between lesion size and progression, and the Spearman coefficient (ρ) was used for correlation strength. Differences between means and correlations were considered to be significant if $P < .05$. Statistical software (SPSS, version 19.0; SPSS, Chicago, Ill) was used.

Results

Pre–Basic Training Analysis

Study group.—Of 55 recruits, 26 had tibial bone stress changes at MR imaging (bone stress changes at time 0), and 29 had no bone stress changes (normal findings at time 0). Of the 26 recruits with bone stress changes, 12 had bilateral findings. In 11 of these recruits, the bilateral findings were approximately symmetric in pattern, measurement, and location; in the remaining recruit, the bilateral findings were symmetric in pattern and location but not in size. Mean age, height, weight, tibial length, and Vo_2max did not significantly differ between recruits with bone stress changes and those with normal findings at time 0: 18.5 years ± 0.8 (standard deviation) versus18.7 years ± 0.8 ($P = .27$), 178 cm ± 5 versus 177 cm ± 6 ($P = .99$), 72 kg ± 6.0 versus 70.3 kg ± 7.7 ($P = .36$),

Figure 1

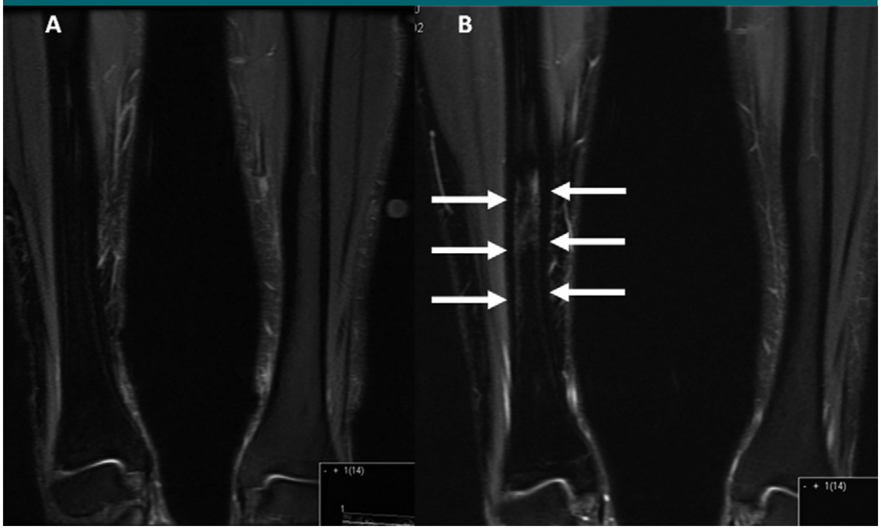

Figure 1: Coronal STIR MR images (2420/34; section thickness, 5 mm; field of view, 350 mm) of the legs of an asymptomatic recruit. *A,* At time 0, the marrow shows normal signal intensity. *B,* At 4 months, right endosteal marrow edema (arrows) has developed.

Figure 2

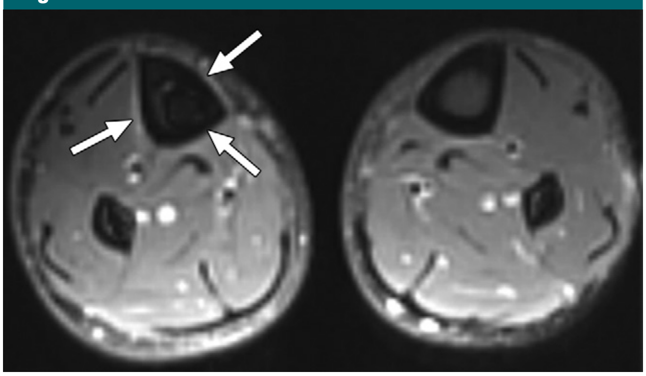

Figure 2: Axial STIR MR images (5000/41; section thickness, 5 mm) at the level of the midcalf show subtle periosteal reaction surrounding the right tibia (arrows), seen as an area of thin circumferential hyperintensity consistent with a grade I stress reaction.

427 mm ± 20 versus 434 mm ± 24 (P = .31), and 55.8 mL·min^{-1}·kg^{-1} ± 5.8 versus 54.6 mL·min^{-1}·kg^{-1} ± 7.0 (P = .16), respectively. In the group of 26 recruits with bone stress changes at time 0, 25 recruits had a grade II stress response at MR imaging and one had a grade I stress response, 20 recruits had endosteal marrow edema, five recruits had patchy bone marrow edema (two recruits had both endosteal and patchy marrow edema), and three recruits had periosteal reaction (Figs 1–3). The location and size of the endosteal bone stress changes in the 21 tibiae of the 20 recruits (one patient had bilateral endosteal asymmetric findings) are summarized in Table 1. Most changes were located in the middle third of the tibia, and their length ranged between 3 and 150 mm. Most patchy bone stress changes were located in the metaphysis, epiphysis, and metadiaphysis. The three periosteal bone stress changes were located in the middle third of the tibia, with lengths ranging between 50 and 110 mm. Notably, all recruits in both the group with bone stress changes and the group without bone stress changes at time 0.

Activity history results are presented in Table 2. In general, most of the recruits' training consisted of aerobic endurance activities (running). No statistically significant differences were observed between the recruits with bone stress changes and those with normal findings at time 0 in terms of training period, number of practices weekly, number of aerobic practices weekly, or the duration of aerobic training prior to induction.

Control subjects.—Of 10 control subjects, one had bone stress changes at time 0 (grade II). These changes were seen as endosteal areas of marrow edema at the junction between the proximal and middle thirds of the tibia and at the junction between the middle and distal thirds of the tibia. Mean age, height, weight, tibial length, and Vo_2max in this group were 18 years ± 0.3, 175 cm ± 6.3, 70 kg ± 12, 429 mm ± 19, and 47 mL·min^{-1}·kg^{-1} ± 8, respectively. Their activity history assessment results were as follows: 3 months ± 2 of training prior to enrollment, with 2 ± 1 practices weekly.

Post–Basic Training Analysis

After 4 months of basic training, bone stress changes were seen in 27 of 55 recruits (bone stress changes at 4 months). All changes were Fredricson grade II. Among the 27 bone stress changes, 18 were observed in recruits at the pre–basic training time point, and nine were newly discovered after basic training. Endosteal edema was seen in 23 of 27 recruits, patchy bone marrow edema was seen in nine recruits, and periosteal reaction was seen in one recruit (Fig 4). Six of the bone stress changes at 4 months had more than one pattern: five consisted of patchy and endosteal edema, and one showed endosteal and periosteal changes.

Most bone stress changes were seen in the middle third of the tibia, usually close to the junction between

Figure 3

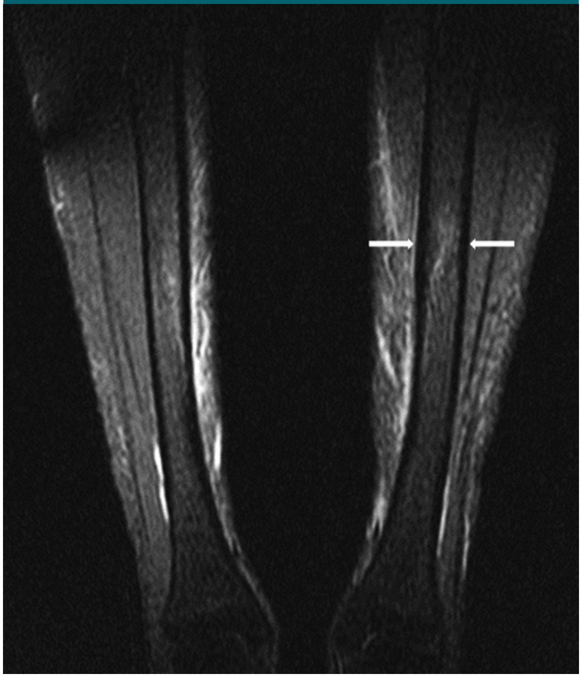

Figure 3: Coronal STIR MR image (2420/34; inversion time msec, 130; field of view, 250 mm) shows grade II stress reaction. There is a patchy area of bone marrow edema in the left tibia (arrows) that is amorphous and cloudlike.

Table 1

The Distribution of Location, Size, and Outcome of Endosteal Bone Marrow Changes

Baseline Location and Size (mm)	Four Months after Basic Training	
	Size (mm)	Outcome
Proximal		
...	...	...
Middle		
150	160	Progressed
116	92	Decreased
102	111	Progressed
100	100	Unchanged
100*	105	Progressed
97	15	Decreased
91	3	Decreased
76	10	Decreased
50	50	Unchanged
50*	75	Progressed
22	22	Unchanged
18	10	Decreased
14	0	Resolved
11	0	Resolved
11	9	Resolved
9	0	Resolved
7	0	Resolved
6	0	Resolved
3	0	Resolved
3	0	Resolved
Distal		
6	0	Resolved

* Bilateral findings in same patient.

the middle and distal thirds at both time points, 0 and 4 months (Fig 5). In 16 of 18 recruits with bone stress changes at both time points, the location was unchanged. In one recruit, the location changed from the junction of the proximal and middle thirds of the tibia to the junction of the middle and distal thirds of the tibia, and in another, the opposite location change occurred. No significant differences were observed between recruits with bone stress changes at 4 months and recruits with normal findings at 4 months in anthropometric measures or in maximal aerobic capacity values.

Results of 4-month Follow-up of Bone Stress Changes at Time 0

Eight of 26 recruits who had positive results at time 0 showed full resolution of the findings at MR imaging. The results of the follow-up of the endosteal findings are shown in Table 1. Four recruits experienced progression: three with endosteal bone stress changes in the middle third of the tibia and one with periosteal changes. In all four recruits, the length of the finding was 100 mm or greater. Bone stress changes smaller than 100 mm were unchanged, decreased, or resolved (except in one recruit who also had progressing contralateral bone stress changes). The Spearman correlation test showed significant correlation ($\rho = 0.52$, $P = .015$) between endosteal lesion size at time 0 and progression at 4-month follow-up MR imaging.

Correlation with Development of Symptomatic Bone Stress Injury

During the 4-month basic training, clinical stress injury developed in six of the 26 recruits with bone stress changes at time 0 (confirmed in five recruits clinically and in one recruit with scintigraphy) and in three of the 29 recruits with normal findings at time 0 (confirmed in one recruit clinically and in two recruits with scintigraphy). However, χ^2 analysis showed no significant differences in clinical stress injury occurrence between the group with bone stress changes at time 0 and the group with normal findings at time 0 ($\chi^2 = 1.6$, $P = .2$). Further analysis revealed that clinical stress injuries were diagnosed as grade II in the group with bone stress changes at time 0 as follows: four of 20 recruits with endosteal reaction, one of five recruits with patchy bone marrow edema, one of two recruits with both patchy and endosteal edema, and no recruits with periosteal reaction.

Bone stress changes occurred in two of 10 control subjects. The single case of marrow edema (grade II) at time 0 resolved in the proximal area and was unchanged in the distal area. There was

Table 2

Activity History for Recruits with Bone Stress Changes on Recruitment Day and Recruits with Normal Findings

Activity History	Recruits with Normal Findings (n = 29)	Recruits with Bone Stress Changes (n = 26)
Training period in past year (mo)	6.7 ± 4.5 (5.0, 8.4)	8.1 ± 4.4 (6.3, 9.9)
No. of practices per week	2.8 ± 1.0 (2.4, 3.2)	2.9 ± 0.6 (2.6, 3.1)
No. of aerobic training exercises per week	2.8 ± 1.2 (2.3, 3.2)	2.5 ± 0.8 (2.2, 2.9)
Aerobic training duration (min)	38.3 ± 17.1 (31.6, 45.1)	35.0 ± 11.9 (30.1, 39.9)

Note. —Data are means ± standard deviations, with 95% confidence intervals in parentheses.

Figure 4

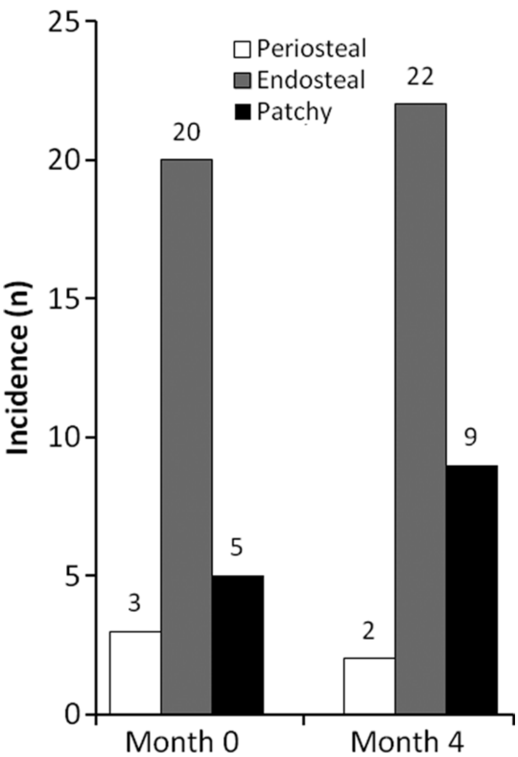

Figure 4: Graph shows incidence of the different MR imaging patterns of bone stress changes—endosteal marrow edema, patchy marrow edema, and periosteal reactions—at time point 0 (before basic training) and after 4 months of basic training.

one recruit who developed patchy marrow edema (grade II) at the proximal tibia epiphysis-metaphysis junction.

Discussion

This study investigated the incidence, location, grade, and pattern of bone stress changes and whether MR imaging parameters correlated with the pretraining activity levels or the future development of symptoms. It was found that asymptomatic bone stress changes did not predict development of clinical symptoms during the 4-month training period. Also, there was no prognostic correlation between a finding of bone stress changes at time 0 and clinical stress injury. These results suggest that the MR imaging findings may represent normal bone remodeling rather than a pathologic process and do not require training modification. The most common type of bone abnormality at MR imaging was endosteal marrow edema, suggesting that it may reflect normal bone turnover. This is compatible with Wolff's law: Normal bones change their morphology as a response to mechanical strain. The changes occur first in the bony trabecula, followed by cortical thickening (27). This is also supported by studies (28) that show tibial cortical thickening and shrinkage of the medullary canal in teenagers as a result of endosteal bone formation induced by physical training. However, we found no reports on the histologic features of normal remodeling.

We did find a significant correlation between the length of the endosteal bone stress changes and MR imaging progression at follow-up: Endosteal lesions larger than 100 mm had a higher rate of progression than lesions smaller than 100 mm. Assuming that some of the overmotivated recruits did not report pain and others did not yet develop symptoms, close clinical follow-up should be considered.

Although small lesions (of a few millimeters) may not comport with typical "stress reactions," as understood by practicing radiologists, for the purpose of this study, any lesion that demonstrated high signal intensity and was not a blood vessel was included in the analysis, as it may represent an early stress response in asymptomatic recruits.

Half of the recruits had bone stress changes at the time of recruitment. Similar or higher bone stress change rates at MR imaging have been reported previously in asymptomatic active athletes (6,19). Typically, a high fitness level is required for acceptance to elite combat units. The highly motivated recruits often self-train intensively, as depicted by their activity history assessment results (Table 2). The low rates of bone stress changes in the control subjects on the day of induction are not surprising, as they were not motivated to comply with

Figure 5

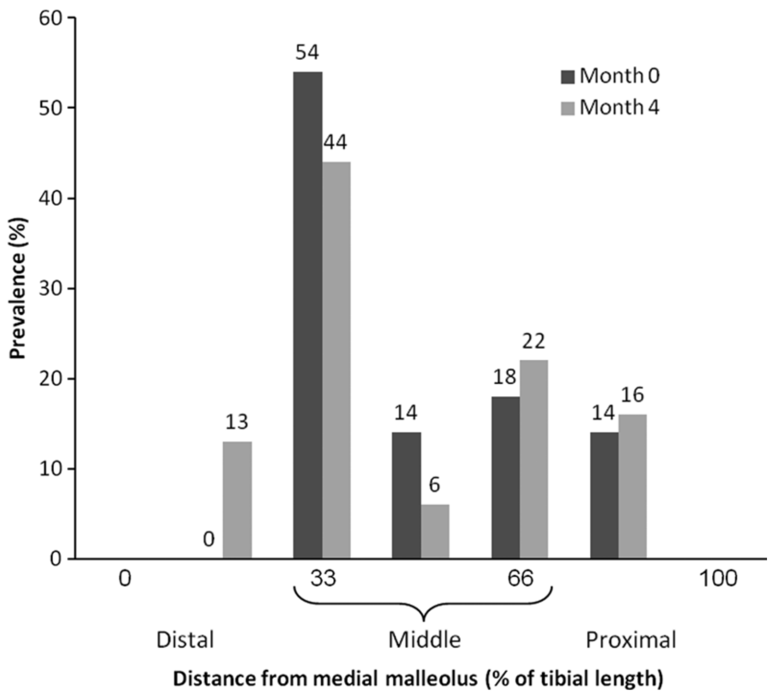

Figure 5: Graph shows the location distribution of bone stress changes along the tibia (proximal = 66%–100% of tibial length measured from the medial malleolus proximally, middle = 33%–66% of tibial length, distal = 0%–33% of tibial length) at time 0 (before basic training) and after 4 months of basic training.

high physical demands. Self-training prior to basic training consisted mainly of running, and the subjects were physically fit, as demonstrated by their Vo_2max. The results of our study could not point to significant differences in activity prior to induction between recruits with bone stress changes and recruits with normal findings. A study performed in 392 Israel Defense Forces elite recruits (29) reported significantly lower rates of stress fractures among recruits who performed high strain and strain rate activities (eg, basketball) prior to induction compared with their counterparts who performed only running. Our study showed that self-training, consisting mainly of running, was not protective and could potentially contribute to the development of bone stress changes. Further research in this direction might lead to better understanding of preinduction bone conditioning. Development of new training programs and distributions of those to the candidates, preferably early enough (years prior to recruitment) might lead to adaptation of the recruits' legs, with a resultant decrease in the rates of clinical stress fractures.

At both time points, no grade III or IV findings were seen. This is supported by the absence of symptoms in our population. Probably, as previously discussed, these areas of bone stress changes reflect normal bone remodeling, which we believe rarely exceeds grade II. Bergman et al (6) also found that findings in asymptomatic runners did not exceed grade II except in two runners, who had grade III findings. In both studies, none of the asymptomatic subjects had grade IV findings.

During the 4-month basic training, fewer recruits developed new bone stress changes as compared with baseline, and the overall rate of bone stress changes was unchanged throughout the 4-month basic training. These findings suggest that the basic training program causes less strain than has been thought, probably owing to the controlled gradual increased intensity. Of note, in other combat units, the rate of clinical stress fractures is between 5% and 30% (1,30).

Surprisingly, there was a paucity of periosteal findings. Because periosteal reaction is given a grade of I in the Fredericson scoring system, we would expect to see more periosteal reactions in addition to the marrow edema of the subects with grade II findings (8). The difference between our results and those of Fredericson et al might be due to the difference in the nature of our populations: We imaged only asymptomatic trainees. Moreover, it is unlikely that the imaging technique is the source of the difference in periosteal reaction incidence.

There were limitations to the study. Although the population group included 55 recruits, only nine developed clinical stress injuries. Although we found a twofold incidence of clinical stress injuries in the group with bone stress changes, it was not statistically significant, either as a result of the small sample size or because MR imaging changes truly do not predict clinical stress injuries. The second limitation was a possible bias in the presence of symptoms, because these overmotivated recruits may dissimulate. Another limitation is the lack of histopathologic examination to prove that areas of hyperintense marrow were consistent with bone remodeling; however, it would be unethical to perform biopsy in asymptomatic patients.

In conclusion, there was a high rate of bone stress changes at MR imaging in highly motivated asymptomatic recruits on the day of recruitment. These changes were located mostly in the distal middle third of the tibia and mainly consisted of endosteal marrow edema. MR imaging findings unaccompanied by symptoms do not predict development of clinical stress injury and probably do not require modification of training, as long as recruits remain asymptomatic. Endosteal lesions larger than 100 mm may reflect early abnormal stress and deserve a close clinical follow-up. The clinical importance of

asymptomatic progressing lesions seen at follow-up MR imaging should be further investigated.

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