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Mobility in Central European Late Eneolithic and Early Bronze Age: tibial cross-sectional geometry

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Abstract

An absence of settlement features during the Central European Corded Ware period (Late Eneolithic, 2900–2300 BC) has been interpreted as a reflection of mobile pastoral subsistence. Recent analyses of the Late Eneolithic archeological context reveal that the Late Eneolithic exhibit evidence of sedentary agricultural activities similar to the Early Bronze Age. Since the archeological analyses are not clear cut, we tested mobility pattern differences between the Late Eneolithic and Early Bronze Age using biomechanical analysis of the tibial midshaft cross-sections. The total sample of the 130 tibiae representing five archaeological cultures was used. The results of the tibial midshaft geometry do not support the hypothesis about different mobility in the Late Eneolithic and Early Bronze Age. This conclusion is supported by nonsignificant differences between the Corded Ware females and the Early Bronze Age females. Higher absolute values for the Corded Ware males should be explained either by stochastic variation or by differing amounts of physical demands despite a generally similar pattern of subsistence of the Late Eneolithic and Early Bronze Age. One of the Early Bronze Age samples, the Wieselburger group, is an exception because the individuals show both reduced overall size and bending resistance of the tibial parameters not only in comparison with the Late Eneolithic but also to the rest of the Early Bronze Age. The results suggest that the behavioral processes which affected the tibial midshaft biology operated during the Late Eneolithic and Early Bronze Age as a mosaic across time and between/within cultures.

Keywords: Biomechanics; Mobility; Bone strength; Late Eneolithic; Early Bronze Age

1. Introduction

There is an ongoing discussion about the absence of the settlement features in the Late Eneolithic cultures—Corded Ware culture (2900–2300 BC [54]) and Bell Beaker culture (2600–2000 BC [54])—which contrasts with abundant evidence of burial sites of the period [32,50,63]. The results of the last decade of intensive and large scale excavations have suggested that the invisibility of the Late Eneolithic settlement features is caused by factors other than preservation [13,35,36,62].

The invisibility of the Late Eneolithic settlement features is traditionally explained as evidence of mobile subsistence strategy, which contrasts with the sedentary life of the subsequent Early Bronze Age groups [63]. This argument is supported by the absence of subterranean features of house structures, storage pits, and ceramic types with either complicated design or ornamentation [63]. All of these factors can be associated with high degree of mobility and contribute to the invisibility of the Late Eneolithic settlements in the archaeological record.

However, the recent revision of the Late Eneolithic archeological finds questioned the absence of settlement features, since at seven sites Turek [60] has demonstrated the presence of Corded Ware pottery fragments associated with settlement activities. Moreover, analysis of the environmental character of the Bohemian Corded Ware sites revealed the association

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with the pleasant wind-sheltered eastern orientation, characteristic fertile loess sub-soils, and proximity to water sources [48]. The environmental association is expected to be well suitable for sedentary agriculture and does not differ from the conditions that were preferred by other Neolithic and Late Eneolithic agricultural groups [32,48,60]. Yet, Neustupný [32] argues that Vencl's [63] evidence concerning the mobility of the Corded Ware groups does not have to be the reflection of differences in mobility and subsistence strategy but rather a reflection of differences in cultural symbolic norms. For Neustupný [32] the Corded Ware groups reserved the vertical axis for symbolic use, which resulted in the absence of subterranean features for profane purposes and abundance of subterranean burial evidence. Moreover, Neustupný [32] and Turek [60] show that sedentary agricultural subsistence for the Corded Ware groups is also supported by the archaeological finds of ploughing traces, artifacts associated with agricultural activities, and impressions of the cereal grains in the Corded Ware archaeological context.

Given the arguments mentioned above, it seems that the mobile subsistence of the Late Eneolithic groups can be rejected. However, ethnological and archaeological accounts show that either the presence of settlement features or finds usually associated with agricultural activities may be associated with the nomadic pastoral subsistence or higher degree of mobility in general [14,20,34]. Mobility is not just a variable associated with a specific form of subsistence and does not have a constant pattern across cultures and time periods [14,20]. Moreover, the mobility of the prehistoric groups must be reconstructed from the archaeological record which has a "static" character and therefore the reconstruction of the mobility pattern does not have to be clear-cut [3,20,34,37,64].

Since the settlement features of the Late Eneolithic groups are not present and archeological evidence of the burial sites are not clear cut to answer the pattern of mobility, it is surprising how little information is actually extracted from human skeletal remains; evidence which is intimately related to daily activities of prehistoric people. Several studies demonstrate that human subsistence strategy is associated with a specific mechanical loading, which affects a long bone adaptive response [7,22,42]. The studies of specific adaptive responses of long bones to mechanical loading are derived from the biomechanical approach [42]. Long bones can be modeled as engineering beams [19] where the geometric structure of their cross-sections is sensitive to the amount and pattern of a particular mechanical loading [25,44]. Compressive and tensile loading can be estimated using the cortical area (CA) in cross-section. Resistance to bending and torsional loading is measured using the cross-sectional second moment of area (I) or polar moment of area (J). Second moment of area is calculated through a specific axis in a cross-section and therefore it is an estimate of mechanical loading in a specific orientation (e.g. antero-posterior versus medio-lateral orientation of loading). The higher degree of mobility which is expected for the Late Eneolithic groups should have created a higher level of physical demands on the long bones. Therefore, the high-mobile subsistence of the Late Eneolithic should have produced long bone cross-section with larger torsional rigidity (J). Moreover, the tibial midshaft of mobile groups has been shown to be more platycnemic in cross-section than the more eurycnemic tibial midshaft of sedentary groups [40,58].

Some studies highlighted ambiguity about the nature of systemic versus localized effects on bone structure remodeling when cortical tissue is studied. For example, thicker cortical tissue has been localized after experimental exercise even in cranial bone that is not directly affected by locomotion [24]. This finding can question the specific and localized effect of mechanical loading [26]. However, there are many clinical, experimental, and bioarchaeological examples of the localized effects of mechanical loading on the human skeleton [16,18,22,38,42,57]. Thus, changes in torsional rigidity as well as resistance in antero-posterior loading of the femoral midshaft induced by differences in mobility between highly mobile pre-agricultural and sedentary agricultural subsistence have been reported by Bridges [6]. Ruff [39] also shows that the femora midshafts of mobile groups tend to be less circular in cross-section, i.e. the mobility index approaches values larger than 1.0 in antero-posterior second moment area relative to medio-lateral second moment of area of the femoral midshaft cross-section.

Our recent study of the 151 femoral midshaft cross-sections selected from the Late Eneolithic and Early Bronze Age sites of the Bohemia, Moravia and Lower Austria shows that there is no substantial difference between the selected groups in mechanical robusticity and shape of the femoral diaphysis [52]. This evidence supports the view of no substantial difference in mobility between the Late Eneolithic and Early Bronze Age groups. The conclusion has been supported by absence of the significant differences in the femoral midshaft cross-sectional parameters in the male sample. However, the Corded Ware males still exhibit the highest absolute mean values of the I_{A-P}/I_{M-L} ratio and antero-posterior second moment of area. Moreover, significant difference among the female samples can be found in femoral medio-lateral second moment of area of the Corded Ware females but the pattern of the cross-sectional geometry difference cannot be directly associated with higher degree of long distance mobility. Similarly, a contradictory result of mobility pattern differences in the Late Eneolithic and Early Bronze Age transition has been drawn from one of the Early Bronze Age groups, the Wieselburger female sample. The Wieselburger female sample exhibits lower cross-sectional size, shape and mechanical robusticity in comparison to the Late Eneolithic and the rest of the Early Bronze Age female samples. Instead of a unidirectional pattern of the Late Eneolithic and Early Bronze Age transition in Central Europe, this evidence supports changes in the mechanical environment across time and between/within cultures. However, to support our previous conclusion, an analysis based on other skeletal parts associated with mobility must be done.

Given the discussion above we can expect that the high degree of mobility versus sedentism of any Late Eneolithic or Early Bronze Age group would produce differences in the distribution of the cross-sectional geometry of midshaft tibia. Therefore, we can expect two opposite possibilities when the cross-sectional geometry of midshaft tibia of the Late Eneolithic (Corded Ware, Bell Beaker) and Early Bronze Age (Únětice, Unterwölbling and Wieselburger) will be compared: (1) the absence of the Late Eneolithic settlement structures contrasts with evidence of Early Bronze Age settlements because of the different degree of mobility between those groups [63]. In this case, the cross-sectional geometry of the tibia midshaft of the Late Eneolithic individuals will show significant differences in the tibia of the Early Bronze Age sedentary individuals; (2) archaeological invisibility of the Late Eneolithic settlements is not a reflection of high degree of mobility but other explanations for the invisibility of Late Eneolithic settlements must be employed [32]. Following the biomechanical background for the cross-sectional development we can expect that the cross-sectional geometry parameters of the Late Eneolithic midshaft tibiae will not show significant differences relative to the Early Bronze Age midshaft tibiae.

2. Materials and methods

2.1. Sample

The sample of 130 tibiae was selected to compare differences in mobility between the Late Eneolithic and Early Bronze Age groups in Central Europe (Table 1). The Bell Beaker and Corded Ware groups represent the Late Eneolithic period while the Únětice, Unterwölbling and Wieselburger groups belong to the Early Bronze Age period. The sites, which were selected for this study, are located in Lower Austria, Moravia and Bohemia. Details about the aforementioned archeological cultures are presented in Buchvaldek [10], Neugebauer [31], Teschler-Nicola [56], Shennan [50]. Although cross-sectional bilateral asymmetry of lower limb tends to be random with respect to side [45,57], right tibiae were preferentially selected. Left tibiae were used in the case where right tibiae were not well preserved. Since the size of the Bell Beaker female sample, Únětice male and female samples and Unterwölbling male sample was reduced due to preservation, we primarily concentrate on comparison of the cross-sectional analyses between the combined Late Eneolithic and Early Bronze Age groups.

2.2. Age and sex estimation

Only adults with closed epiphyses were included in the analysis to prevent possible inconsistencies caused by behavioral impact on long bone cross-sectional geometry. Sex of the Late Eneolithic and Early Bronze Age individuals was allocated both by metric and morphological assessments of the pelvis, femora, tibiae and humeri following the approach of primary and secondary sex analysis [30]. The primary analysis of sex allocation is based on a set of five pelvic measurements and two discriminant function analyses [9,33] as well as on five pelvic morphological features [8]. Fourteen discriminant functions were computed using primary identified sample and different combination of pelvic, femoral, tibial and humeral measurements to obtain the secondary sex allocation. The correct classification of the secondary discriminant functions ranges between 89 and 99% of the primary allocated individuals. The final sex of an individual was allocated only when the consistency between results of the primary and secondary analysis was reached. The individuals with inconsistencies between the primary and secondary analyses were treated as indeterminable and were used only when the total sample of the Late Eneolithic and Early Bronze Age was used.

Changes in perception of gender in mortuary practices have been reported during the Late Eneolithic and Early Bronze Age [61]. We assume that there are several factors beyond mobility that are involved in changes of gender/sexual dimorphism. The control for these factors is out of the scope of our testing model. Therefore, males and females are further

Table 1
Structure of the Central European sample used in the study[a]

Culture	Dating and sites	N_T (N_F; N_M)[e]
Bell Beaker (BBC)	(LE; 2600–2000 BC)[b] Brandýsek; Březno (BBC); Dolní Věstonice; Holubice IV; Kbely; Kněževes (BBC); Lochenice; Malá Ohrada (BBC); Pavlov; Plotiště; Radovesice; Tödling; Tuchoměřice (BBC); Žabovřesky; Židovice	19 (5; 10)
Corded Ware (CWC)	(LE; 2900–2300 BC)[b] Franzhausen I (CWC); Blšany; Brozany; Březno (CWC); Kobylisy; Kučlín; Liběšice; Malé Březno; Malá Ohrada (CWC); Most; Obrnice; Pohořelice; Poplze; Postoloprty; Prosetice; Rousínov; Široké Třebčice; Tučapy; Tuchoměřice (CWC); Veliká Ves; Vikletice; Vrbice; Vyškov	25 (9; 13)
Únětice	(EBA; 2200–1820 BC)[b] Bernhardsthal; Groszmugl; Hobersdorf; Schleinbach; Unterhautzenthal; Würnitz	22 (8; 8)
Unterwölbling (Unter)	(EBA; 2020–1770 BC)[c] Franzhausen I (U); Gemainlebarn F; Melk; Pottenbrunn	33 (12; 8)
Wieselburger (Wiesl)	(EBA; approximately 2000–1700 BC)[d] Hainburg	31 (16; 12)
Late Eneolithic (LE)		44 (14; 23)
Early Bronze Age (EBA)		86 (36; 28)

[a] See geographic demarcation and definition of Central Europe in [51].
[b] The radiocarbon dates are given as an estimate of the 68.2% confidence interval from [54].
[c] The radiocarbon dates is estimated based on sample of the 98 radiocarbon dates from Franzhausen I (U) and is given as and estimate of the 68.2% confidence interval (Stadler, personal communication).
[d] No radiocarbon dates available yet. The numeric date is approximated based on relative chronology and archeological context of the Early Bronze Age sites from the Lower Austria (Stadler, personal communication).
[e] T, total (indeterminable included); F, Female; M, Male.

analyzed separately and mobility is studied not as a phenomenon connected with the changes of sexual dimorphism.

2.3. Linear measurements

Two linear osteometric measurements were used for size and beam length standardization (see below). Femoral head diameter, which was used for the estimate of body mass, was taken following the standard osteometric approach [5]. The definition of tibial biomechanical length as a beam scaling parameter follows Trinkaus and Ruff [58, p. 1291] (see also [44]).

2.4. The diaphyseal sections and computation of cross-sectional parameters

Only individuals who preserved both tibial biomechanical length and a complete midshaft were CT scanned by CT Hi-Speed Dxi (General Electric, Milwaukee, WI) at 50% of tibial biomechanical length. Prior to scanning, the tibiae were oriented in a standardized position with respect to antero-posterior and medio-lateral plane using the approach specified by Ruff and Hayes [44] and Ruff [43]. Final CT scan image consists of a 2 mm thick slice with resolution of 512 × 512 pixels which gives a pixel dimension of 0.196 mm.

The CT scan images of the 50% cross-sections were further processed using the software for digitizing and computing biomechanical parameters developed by the authors (CT-i software; [49]). The manual setting of the periosteal and endosteal contour points was used. It has been shown previously that such an approach is free of inter- and intra-observer error [49].

2.5. The cross-sectional parameters

The cross-sectional geometry of tibial diaphysis was estimated using CT-i values of areas, second moments of area, and polar moment of area. Cortical area (CA) estimates cross-sectional rigidity in axial compression and tension [22,42], total area (TA) is the area within the outer subperiosteal boundary. Given the fact that long bones of the lower limb are also affected by forces other than axial loading [12], second moments of area (I) were used to evaluate resistance to bending rigidity [22,42]. The antero-posterior orientation of the tibiae was approximated in some points and therefore maximum second moment of area and the one perpendicular to it (I_{max}, I_{min}) were used instead of the anatomically oriented values of second moments of area (I_{A-P}, I_{M-L}). However, the maximum and minimum values are close to anatomically oriented second moments of area [58]. Consequently, polar moment of area (J) as a sum of any two second moments of area perpendicular to each other is used to estimate torsional rigidity [22,23,42] and overall bending strength. It has also been shown that the polar moment of area is a good estimate of skeletal robusticity when appropriately scaled by a mechanically relevant measure of body size [47]. Finally, the ratio of I_{max}/I_{min} was used to compare diaphyseal shape [22,42].

2.6. Size standardization

To compare the impact of mechanical loading on diaphyseal parameters, an appropriate means of scaling to body size must be adopted [47]. The mechanically relevant measure of body size in axial loading and bending/torsional loading is expected to be body mass [42,47]. In addition to body mass, moment arm length has to be also included in the size standardization when bending and torsional loading is considered [12,42,47]. Therefore, total subperiosteal area and cortical area were scaled using body mass, while second and polar moments of area were adjusted by body mass times moment arm length [47,58].

Tibial biomechanical length was used as a moment arm length (see above) [44]. Body mass was estimated using femoral head breadth and following equations: (1) $BM = 2.239 \times FHB - 39.9$ [29]; (2) $BM = 2.268 \times FHB - 36.5$ [15], where BM is body mass and FHB is femoral head diameter in mm. The measurements are raw (not-logged) data and femoral head diameter is in mm. The arithmetic mean of the result of equations (1) and (2) was computed as a final body mass estimate (see for details [46]). The femoral head breadth approach to estimate body mass was used instead of stature + bi-iliac estimate [41] since bi-iliac breadth is poorly preserved in the studied samples (only 22% of the total sample yield preserved bi-iliac breadth; preservation of bi-iliac breadth in some samples is below 5%; e.g., Unterwölbling = 4.2% of preserved bi-iliac breadth). Moreover, femoral head breadth has been shown to be a good estimate of body mass in skeletal samples of fossil hominins [2,15,29,46] and is well correlated with body mass estimated by stature + bi-iliac approach [46].

2.7. Statistical treatment

Statistica 6.0 (StatSoft, 1984–2001) and Excel 97 (Microsoft Corporation, 1985–1997) were used for the basic statistical treatment.

Two-way ANOVA with sex and culture as grouping factors was used to test the effect of these variables on selected biomechanical parameters of the studied samples. Post-hoc Bonferroni and Fisher LSD tests were employed to compare individual post-hoc differences among sex/cultural means of samples.

The I_{max}/I_{min} index was compared when diaphyseal shape of the tibial midshaft cross-section was studied. Given the fact that indices generally violate several assumptions for application of parametric tests, descriptive parameters of the I_{max}/I_{min} index were estimated by the bootstrap procedure. Mean and 95% confidence interval for mean of I_{max}/I_{min} index were computed by Resampling Stats for Excell 2.0 (Resampling Stats, Inc.) and further processed in Excel 97 (Microsoft Corporation, 1985–1997).

Since the scaling of cross-sectional parameters is based on continuous variables such as body mass and body mass times tibial biomechanical length and all these parameters are measured with error, the reduced major axis model was used to compare bivariate relationship of the studied variables [1,11,21,27,53]. Reduced major axis was computed by Software for Reduced Major Axis Regression [4]. Slope and intercept were estimated by 95% confidence interval using the bootstrap technique.

The Quick Test was used to compare differences in distribution along reduced major axes between selected samples [59]. The test is arranged as Fisher's exact two-tailed test when the number of individuals above the reduced major axis is compared with the number of individuals below the reduced major axis regression through the pooled sample. Data for Fisher's exact two-tailed test were prepared in Excel tables and StatXact 6.1 software (Cytel Software Corporation, 1989–2002) was used to run Fisher's exact test. The advantage of StatXact 6.1 software lies in computation of exact values instead of approximation by asymptotic values [28].

3. Results

3.1. Tibial biomechanical length

Tibial biomechanical lengths are given for the combined Late Eneolithic and Early Bronze Age sample in Table 2, and for the separate samples in Table 3. The descriptive characteristics are shown both for the total sample (pooled sex including indeterminate individuals) and separated by sex. On average, the Late Eneolithic has significantly longer tibial lengths than the Early Bronze Age group when the total combined sample is studied (Table 2). In contrast, there is no significant difference between the sex-specific samples of the combined Late Eneolithic and Early Bronze Age. The analysis of the separate samples reveals a significant decrease of the tibial length for the Wieselburger sample when sex and indeterminate individuals are pooled (the total sample comparison) (Table 3). The trend of the reduction of the tibial length in the Wieselburger sample is partly supported in the male samples but nonsignificantly different in the female samples.

Given the above results, it is apparent that the average decrease of the tibial lengths of the combined Late Eneolithic and Early Bronze Age groups was not uniform because of temporal changes and/or cultural transition between the Late Eneolithic and Early Bronze Age, since a significant decrease is seen only in the Wieselburger sample. Since the tibial biomechanical length is likely affected by environmental factors (e.g., growth, subsistence and disease history, etc.; see [22]), the environmental stress, which influences the tibial lengths, is similar in the Late Eneolithic and some of the Early Bronze Age archeological groups but different in the Wieselburger group.

3.2. Relative cortical area and axial robusticity

The descriptive characteristics of the adjusted cross-sectional areas of the tibial midshaft are shown for the combined sample comparison in Table 2 and for the separate sample analysis in Table 3. The bivariate distributions of tibial

Table 2
Descriptive sample characteristics of tibial biomechanical length, body mass and midshaft tibial cross-sectional properties for the combined samples of the Late Eneolithic and Early Bronze Age groups (mean (*N*) ± SE)

Parameter[a]	Total (LE)	Total (EBA)	B/LSD[b]	Females (LE)	Females (EBA)	B	LSD	Males (LE)	Males (EBA)	B	LSD
Ti-BML	357.5 (44) ± 3.33	345.0 (86) ± 2.54	***	335.6 (14) ± 3.06	329.0 (36) ± 2.56			368.5 (23) ± 4.03	364.9 (28) ± 3.75		
TA adj	697.7 (42) ± 11.73	651.5 (67) ± 7.87	***	681.7 (14) ± 19.76	637.4 (31) ± 13.05		*	717.2 (21) ± 15.93	663.5 (22) ± 11.93		*
CA adj	498.8 (42) ± 9.81	468.7 (67) ± 6.34	**	474.4 (14) ± 16.93	453.2 (31) ± 9.73			513.9 (21) ± 13.51	486.9 (22) ± 10.08		
MA adj	198.9 (42) ± 6.57	182.8 (67) ± 4.93	*	207.2 (14) ± 12.62	184.2 (31) ± 7.39			203.3 (21) ± 8.30	176.6 (22) ± 6.67		*
I_{max} adj	1027.0 (42) ± 36.8	887.7 (67) ± 24.43	***	889.0 (14) ± 50.30	772.2 (31) ± 31.24		*	1153.7 (21) ± 49.9	1005.5 (22) ± 27.9		*
I_{min} adj	451.1 (42) ± 15.45	387.7 (67) ± 9.68	***	398.9 (14) ± 25.87	360.5 (31) ± 12.42			488.1 (21) ± 19.97	433.1 (22) ± 18.19		*
J adj	1478.1 (42) ± 49.1	1275.4 (67) ± 31.7	***	1287.9 (14) ± 73.9	1132.7 (31) ± 41.9		*	1641.8 (21) ± 63.2	1438.6 (22) ± 39.3	*	*

[a] Ti-BML, tibial biomechanical length; TA, total subperiosteal area; CA, cortical area; MA, medullary area; I_{max}, maximum second moment of area; I_{min}, minimum second moment of area; J, polar moment of area. Tibial biomechanical length is in mm, bone areas are in mm^2 and second moments of area are in mm^4. Bone areas are size-standardized by body mass × 100; second moments of area are size standardized by body mass × tibial biomechanical length and multiplied by 1000.

[b] ANOVA post-hoc tests: B, Bonferroni post-hoc test; LSD, Fisher LSD post-hoc test; *<0.05, **<0.01, ***<0.001.

Table 3
Descriptive sample characteristics (mean (N) ± SE) and post-hoc ANOVA tests comparison of the separate groups of the Late Eneolithic and Early Bronze Age

Parameter (T)[a]	Bell Beaker	Corded Ware	Únětice	Unterwölbling	Wieselburger	Bonferroni[b]	Fisher LSD[b]
Ti-BML	358.9 (19) ± 5.10	356.5 (25) ± 4.47	347.3 (22) ± 5.22	350.5 (33) ± 4.16	337.6 (31) ± 3.81	1/5*** 2/5***	1/5*** 2/5*** 4/5*
TA adj	703.1 (19) ± 18.56	693.2 (23) ± 15.27	682.4 (14) ± 15.64	674.3 (23) ± 11.88	619.6 (30) ± 10.85	1/5*** 2/5*** 3/5* 4/5*	1/5*** 2/5*** 3/5** 4/5**
CA adj	497.5 (19) ± 15.34	500.0 (23) ± 12.98	487.8 (14) ± 8.27	476.7 (23) ± 11.62	453.6 (30) ± 9.80	2/5*	1/5** 2/5** 3/5*
MA adj	205.7 (19) ± 8.21	193.3 (23) ± 9.92	194.6 (14) ± 12.93	197.6 (23) ± 8.79	165.9 (30) ± 5.06	1/5** 4/5*	1/5*** 2/5** 3/5* 4/5**
I_{max} adj	999.7 (19) ± 50.02	1049.5 (23) ± 53.5	1010.5 (14) ± 29.30	920.3 (23) ± 43.94	805.4 (30) ± 35.03	1/5** 2/5*** 3/5**	1/5*** 2/5*** 3/5*** 4/5* 2/4*
I_{min} adj	467.6 (19) ± 23.96	437.5 (23) ± 20.15	410.5 (14) ± 17.43	392.7 (23) ± 13.66	373.2 (30) ± 16.95	1/5*** 2/5* 1/4*	1/3* 1/4** 1/5*** 2/5**
J adj	1467.3 (19) ± 71.2	1487.0 (23) ± 69.1	1421.0 (14) ± 36.23	1313.0 (23) ± 53.67	1178.5 (30) ± 49.5	1/5*** 2/5*** 3/5*	1/5*** 2/5*** 3/5** 4/5* 1/4* 2/4*
Parameter (F)							
Ti-BML	338.5 (5) ± 6.74	334.1 (9) ± 3.20	328.3 (8) ± 3.86	332.3 (12) ± 5.09	327.0 (16) ± 3.96		
TA adj	705.5 (5) ± 48.27	668.5 (9) ± 16.71	731.4 (5) ± 19.98	671.0 (11) ± 14.47	581.4 (15) ± 10.65	1/5* 2/5* 3/5** 4/5*	1/5*** 2/5** 3/5*** 4/5***
CA adj	486.2 (5) ± 39.24	467.9 (9) ± 16.79	501.7 (5) ± 16.15	472.3 (11) ± 16.52	422.9 (15) ± 10.52		1/5* 2/5* 3/5** 4/5*
MA adj	219.3 (5) ± 20.47	200.5 (9) ± 16.45	229.6 (5) ± 17.20	198.7 (11) ± 10.01	158.5 (15) ± 7.36	3/5*	1/5** 2/5* 3/5*** 4/5*
I_{max} adj	893.9 (5) ± 125.60	886.3 (9) ± 44.83	1009.5 (5) ± 64.17	822.1 (11) ± 39.68	656.4 (15) ± 25.98	3/5**	1/5* 2/5** 3/5*** 4/5*
I_{min} adj	429.8 (5) ± 61.68	381.7 (9) ± 23.06	443.7 (5) ± 25.80	385.3 (11) ± 17.77	314.6 (15) ± 10.34		1/5* 2/5** 3/5** 4/5*
J adj	1323.7 (5) ± 186.8	1268.0 (9) ± 63.27	1453.2 (5) ± 81.48	1207.4 (11) ± 51.16	971.0 (15) ± 34.18	3/5**	1/5** 2/5** 3/5** 4/5* 4/3*
Parameter (M)							
Ti-BML	365.1 (10) ± 7.23	371.2 (13) ± 4.59	371.1 (8) ± 6.65	372.8 (8) ± 7.30	355.6 (12) ± 5.02		2/5* 4/5**
TA adj	700.9 (10) ± 23.05	732.0 (11) ± 22.09	666.4 (6) ± 17.22	683.1 (4) ± 45.81	655.5 (12) ± 14.91		2/5** 2/3*
CA adj	493.4 (10) ± 17.71	532.5 (11) ± 19.16	472.2 (6) ± 11.31	515.4 (4) ± 40.75	484.7 (12) ± 11.86		2/5* 2/3*
MA adj	207.5 (10) ± 8.94	199.5 (11) ± 13.94	194.2 (6) ± 10.15	167.7 (4) ± 25.78	170.8 (12) ± 7.25		1/5*
I_{max} adj	1067.2 (10) ± 64.1	1232.3 (11) ± 69.8	1011.9 (6) ± 48.83	1091.0 (4) ± 103.24	973.8 (12) ± 30.09	2/5*	2/1* 2/3* 2/5**
I_{min} adj	474.9 (10) ± 29.95	500.2 (11) ± 27.54	408.1 (6) ± 28.08	450.3 (4) ± 30.33	439.9 (12) ± 29.21		2/3*
J adj	1542.1 (10) ± 88.4	1732.5 (11) ± 84.4	1420.0 (6) ± 54.32	1541.4 (4) ± 132.97	1413.7 (12) ± 52.20	2/5*	2/3* 2/5*

[a] See Tables 1 and 2 for abbreviations and computation details.
[b] The numbers indicate the pair significance between the respective groups; * <0.05, ** <0.01, *** <0.001.

midshaft cortical area against total area are given in Fig. 1 and the distribution of tibial midshaft cortical area relative to body mass in Fig. 2.

On average, the adjusted cross-sectional areas of the tibial midshaft are significant in the combined samples when sex and indeterminate individuals are pooled (Table 2). When divided by sex, only adjusted total subperiosteal area is significant both for males and females and adjusted medullary area is significant for male groups of the combined samples. Adjusted cortical area remains nonsignificant between the combined male and female samples. The means of the cross-sectional areas of the separate groups are mostly equivalent except the Wieselburger sample (Table 3). The Wieselburger individuals have significantly lower values of the cross-sectional areas in comparison to the Late Eneolithic and rest of the Early Bronze Age groups both in male and female analyses. The significant decrease of total subperiosteal area and cortical area in the Únětice female group in comparison to the Corded Ware individuals should be considered approximate because the sample of the Únětice is small ($n = 6$).

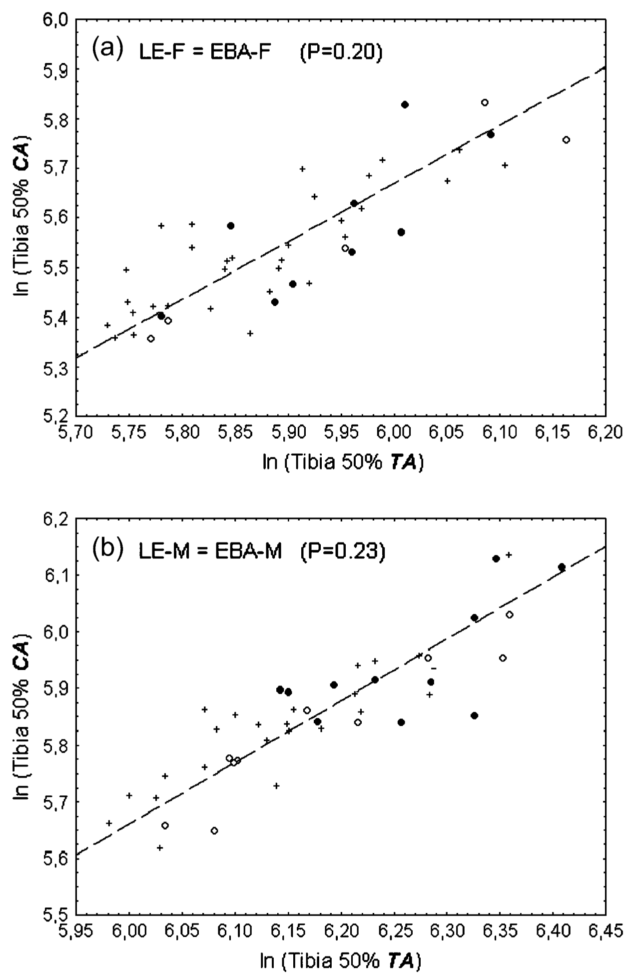

Fig. 1. Cortical area (CA) of tibial midshaft relative to total area (TA) in female (a) and male sample (b). Circles, Late Eneolithic (LE) (filled circles: Corded Ware group; open circles: Bell Beaker group); crosses, Early Bronze Age group. Reduced major axis line plotted through the pooled sample; result of Quick Test comparisons about this line shown.

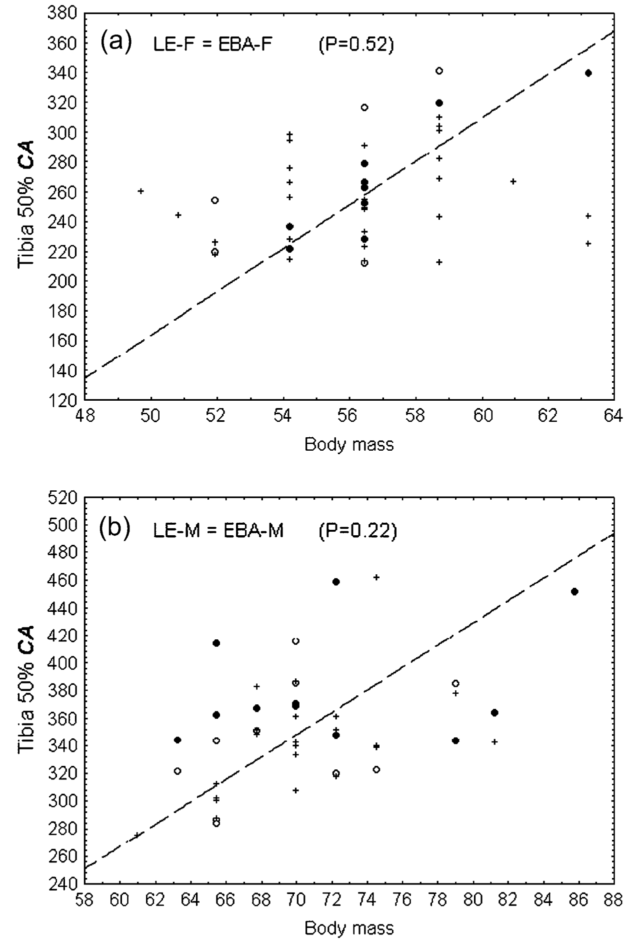

Fig. 2. Cortical area (CA) of tibial midshaft relative to body mass (BM) in female (a) and male sample (b). See Fig. 1 for description and computation details.

The Late Eneolithic has no significantly greater tibial midshaft cortical area relative to total subperiosteal area (Fig. 1). Similarly nonsignificant is bivariate distribution of the cortical area relative to body mass between the Late Eneolithic and Early Bronze Age individuals (Fig. 2). Thus, the Late Eneolithic individuals have a similar amount of cortical bone in comparison to either total subperiosteal area or body mass.

To conclude, the Corded Ware individuals, and the Late Eneolithic group in general, are similar in cross-sectional areas with the Early Bronze Age group, with exception of the Wieselburger group. Again, the results support our previous conclusion concerning the difference of the Wieselburger individuals to the rest of the studied samples and also the absence of temporal trend affecting the parameters of the cross-sectional areas between the Late Eneolithic and Early Bronze Age period.

3.3. Torsional robusticity

The sample characteristics of adjusted polar moment of area, an estimate of the overall bending/torsional robusticity, are shown for the combined samples in Table 2 and for the separate samples in Table 3. The bivariate distribution of tibial midshaft polar moment of area relative to the product of body mass and tibial biomechanical length is given in Fig. 3.

On average, adjusted polar moment of area shows a significant decrease between the combined samples of the Late Eneolithic and Early Bronze Age when the total as well as female or male combined samples are studied (Table 2). Analysis of variance reveals the two patterns in mean adjusted polar moment of area (Table 3). First, the Wieselburger sample again reveals a significant decrease of the cross-sectional parameter in comparison to the rest of the Late Eneolithic and Early Bronze Age groups when the total or female samples were studied. The decrease of the Wieselburger male sample is less pronounced and is only significantly different from the Corded Ware male sample. Second, the Corded Ware males have the largest absolute mean value for the adjusted polar moment of area. However, the average is significant only in the case of the Wieselburger and Únětice males. Given the uncertainties resulting from the small sample size of the Únětice males, the sample should be enlarged before evaluation. Similarly, small sample size could also resulted in significant difference of the Únětice and Unterwölbling female samples.

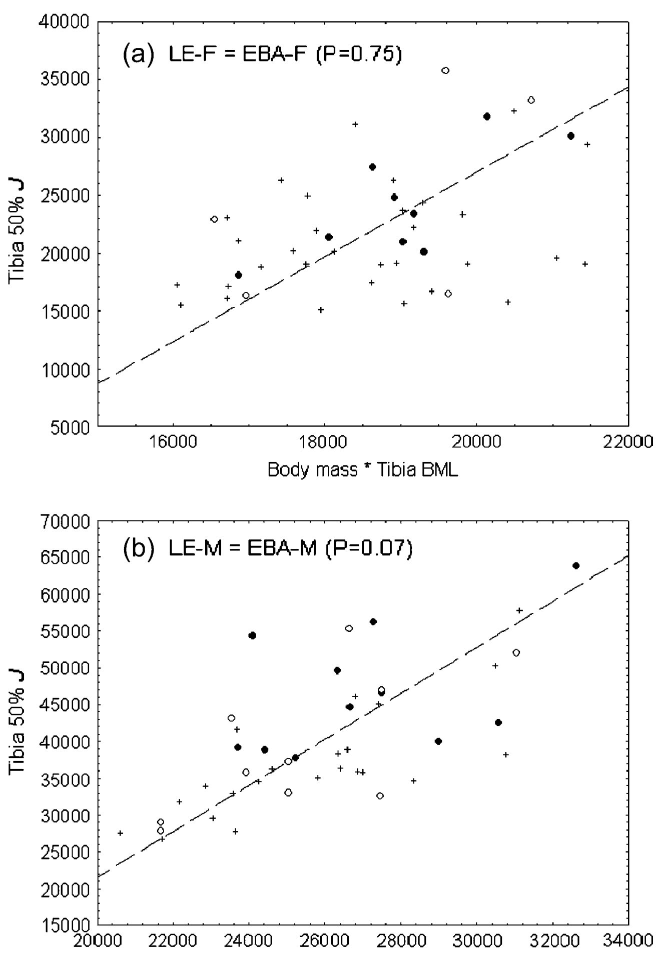

Fig. 3. Polar moment of area (J) of tibial midshaft relative to body mass (BM) and biomechanical length (BML) in female (a) and male sample (b). See Fig. 1 for description and computation details.

The bivariate distribution of polar moment area adjusted by the product of body mass and tibial biomechanical length is nonsignificant between the Late Eneolithic and Early Bronze Age females (Fig. 3). The Late Eneolithic males are near-significantly ($P = 0.07$) above the pooled reduced major axis of the Late Eneolithic and Early Bronze Age. Thus, the results of the bivariate analysis are different than those for the mean analyses. The bivariate distribution of the Late Eneolithic and Early Bronze Age samples does not support the hypothesis that there is a temporal decrease in polar moment of area (i.e., overall bending/torsional robusticity). The conservative nature for the Quick Test of the bivariate distribution may explain the contradiction.

3.4. Diaphyseal shape

Since the polar moment of area sums perpendicular bending rigidity measures (i.e., maximum and minimum second moments of area) and therefore is an overall measure of the bending/torsional robusticity, the individual second moments of area and their pattern of distribution in the tibial midshaft cross-section are also compared. The descriptive sample characteristics of adjusted maximum and minimum second moments of area are given for the combined Late Eneolithic and Early Bronze Age samples in Table 2 and for the separate samples in Table 3. The bivariate distributions of the second moments of area relative to the product of body mass and tibial biomechanical length are shown in Figs. 4 and 5.

On average, the combined Late Eneolithic total and male samples have significantly greater maximum and minimum second moments of area than the combined Early Bronze Age groups (Table 2), although the difference in the comparison of males is not as marked as in the total sample comparison. The combined female Late Eneolithic sample is significantly greater than the Early Bronze Age only in adjusted maximum second moment of area. In analyses of the separate means, the Wieselburger female sample has significantly smaller means of both adjusted maximum and minimum second moments of area than the Late Eneolithic and the rest of the Early Bronze Age female samples (Table 3). On average, the Corded Ware females remains significantly higher resistant only when the Wieselburger sample is compared and show little variation toward more bending resistant tibial midshaft cross sections in comparison with the rest of the female samples. In contrast, the Corded Ware males have on average significantly greater maximum second moment of area (except the Unterwölbling male sample) and average values of the minimum second moment of area are significantly greater between the Corded Ware and Únětice males. Thus, while second moments of area are similar for the Corded Ware females and rest of the studied samples, the Corded Ware males are more bending resistant in the maximum second moment of area. The only exception to the pattern of bending resistance of the Corded Ware females and males is in the Wieselburger sample, which shows the lowest values in each

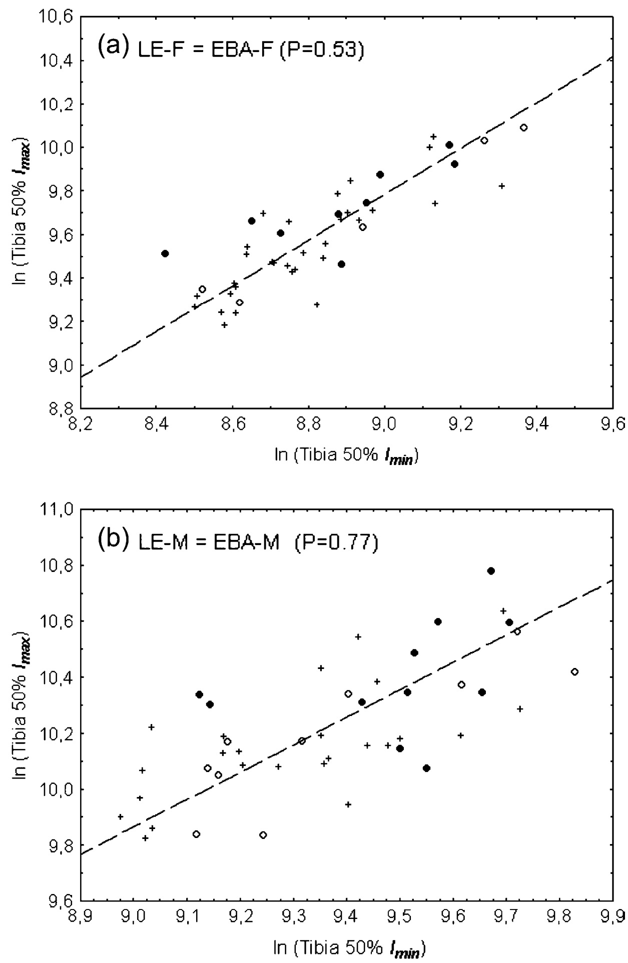

Fig. 4. Maximum second moment of area (I_{max}) of tibial midshaft relative to minimum second moment of area (I_{min}) in female (a) and male sample (b). See Fig. 1 for description and computation details.

comparison of the second moments of area. The bivariate distribution of second moments of area relative to the product of body mass and tibial biomechanical length remains nonsignificant between the Late Eneolithic and Early Bronze Age in all of the comparison (Figs. 4 and 5). However, the Corded Ware males are distributed slightly above the pooled reduced major axis in maximum and minimum second moments of area, while females are slightly below the axis in the minimum second moment of area comparison.

The shape of the distribution of differences in bending rigidity between the Late Eneolithic and Early Bronze Age groups were estimated by the I_{max}/I_{min} ratio (e.g., the mobility index). It has been shown in previous studies that more mobile groups have higher maximum second moment of area relative to minimum second moment of area [40]. Therefore, if the Corded Ware individuals are more mobile (and the Late Eneolithic individuals in general), we should expect higher values for the I_{max}/I_{min} ratio. The descriptive sample characteristics of the I_{max}/I_{min} ratio are presented in Table 4. The bivariate distribution of maximum second moment of area relative to minimum second moment of area is shown in Fig. 6. On average, the 95% bootstrap confidence interval of means overlap between the combined Late Eneolithic and Early Bronze Age samples as well as between the separate groups (Table 4). Both Corded Ware males and females exhibit large the mean values of the I_{max}/I_{min} ratio. In contrast the Bell Beaker groups have the smallest mean values of the I_{max}/I_{min} ration. The bivariate distribution of maximum second moment of area relative to minimum second moment of area is nonsignificant for all the comparisons of the Late Eneolithic and Early Bronze Age samples (Fig. 6). However, the Corded Ware females are visually distributed more below the pooled reduced major axis while the Corded Ware males more above this axis.

Thus, the mobility index is nonsignificant between the studied groups. The Corded Ware and Bell Beakers have similar distribution of maximum and minimum second moment of area compared to the Early Bronze Age groups. The trend is supported when individual second moments of area are compared. Only the Wieselburger sample shows a significant decrease in the individual second moments of area in comparison with the Early Bronze Age. Both analyses of the mobility index and ANOVA means show that the Corded Ware males have slightly stronger the tibial diaphyses in maximum second moment of area. The trend is significant in

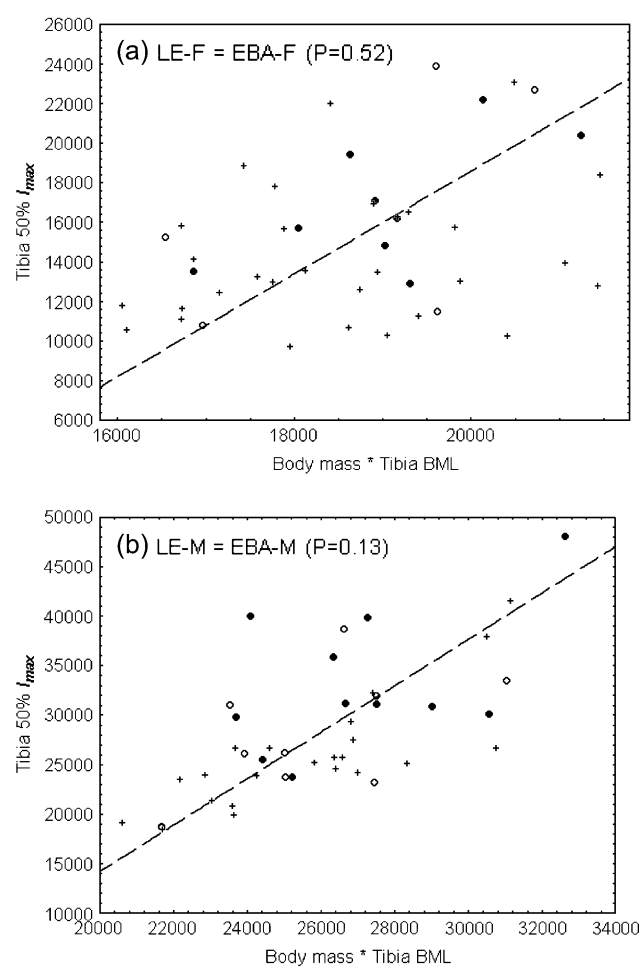

Fig. 5. Maximum second moment of area (I_{max}) of tibial midshaft relative to body mass (BM) and biomechanical length (BML) in female (a) and male sample (b). See Fig. 1 for description and computation details.

Table 4
Mean and the 95% mean confidence interval of I_{max}/I_{min} ratio for the Late Eneolithic and Early Bronze Age groups in Central Europe[a]

	Females		Mean confidence interval		Males		Mean confidence interval	
Group	N	Mean	+95%	−95%	N	Mean	+95%	−95%
Bell Beaker	5	2.091	1.992	2.211	10	2.275	2.076	2.434
Corded Ware	9	2.358	2.143	2.569	11	2.524	2.228	2.825
Únětice	5	2.293	2.042	2.476	6	2.544	2.168	2.986
Unterwölbling	11	2.144	1.974	2.333	6	2.421	2.211	2.654
Wieselburger	15	2.090	1.985	2.184	12	2.289	2.052	2.497
Late Eneolithic	14	2.255	2.104	2.440	21	2.402	2.227	2.593
Early Bronze Age	31	2.147	2.055	2.232	24	2.386	2.223	2.559

[a] The mean and 95% mean confidence interval of I_{max}/I_{min} ratio is given as a bootstrap estimate (see text for details).

post-hoc analyses of ANOVA test. However, given the small sample size of some of the studied groups, the pattern should be considered with caution.

4. Discussion

The results of our analyses indicate that the tibial cross-sectional parameters of the Late Eneolithic and Early Bronze Age samples are similar in regard to expected differences in mobility and, therefore, do not support the hypothesis about different mobility patterns in both periods. The analyses of the tibial midshaft cross-sections confirm our previous conclusion based on femoral cross-sections that overall mobility differences between the Late Eneolithic and Early Bronze Age periods were minute and the changes in mobility between the two periods were not unidirectional, i.e. diachronic.

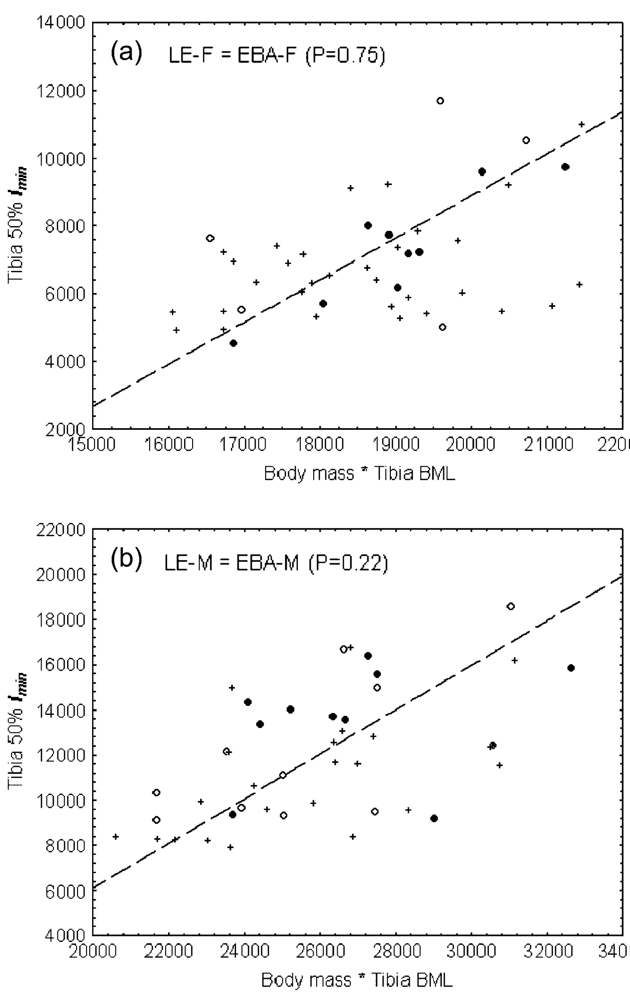

Fig. 6. Minimum second moment of area (I_{min}) of tibial midshaft relative to body mass (BM) and biomechanical length (BML) in female (a) and male sample (b). See Fig. 1 for description and computation details.

The Corded Ware females show similar amounts of bending and torsional rigidity as other studied groups except the Wieselburger females. Thus, higher bending resistance of the Corded Ware females which has been found in the femoral midshaft medio-lateral second moment of area in our previous study is not supported by tibial cross-sections. Since the tibia is less affected by body proportion (i.e., body breadth), the higher bending resistance for the femoral midshaft probably reflects changes in body shape than differences in activity. However, this statement has to be tested using other analyses in future.

In contrast, the results of the tibial midshaft cross-section of the Corded Ware males support the conclusion based on femoral cross-sections. In absolute values, the Corded Ware males have larger antero-posterior as well as maximum second moment of area and resultant index of mobility than some of the Early Bronze Age groups. However, the absolute increase of the bending rigidity of the Corded Ware males is not significantly different in all of the femoral midshaft cross-section analyses and in the tibial I_{max}/I_{min} ratio. The only significant increase of the bending rigidity remains the post-hoc ANOVA Fisher LSD test of the tibial midshaft maximum second moment of area. It is unclear if the increase of the absolute values of the femoral and tibial antero-posterior (maximum) bending resistance of the Corded Ware males is either stochastic variation or has some behavioral meaning, which may be masked by the small size of our samples. We used the European Mesolithic males as a model of more regionally oriented mobility, since the European Mesolithic reflects foraging way of life characterized by intense exploitation of regional resources [55] and subsequent reduction of mobility between the Upper Paleolithic and Mesolithic (see [17]). The Corded Ware males have on average 25% lower tibial midshaft I_{A-P}/I_{M-L} ratio than the European Mesolithic males (data from [17]). This indicates that the higher bending resistance of the Corded Ware males when compared to the Early Bronze Age is more affected by either stochastic variation or variation within similar pattern of subsistence. Given the fact that our testing model takes into consideration only two extreme variants of mobility (i.e., fully mobile groups of the Late Eneolithic and fully sedentary groups of the Early Bronze Age), we can expect that the variation of subsistence strategy between the Corded Ware and Early Bronze Age is not a case of the two extreme variants. Therefore, if some stochastic variation is not included, the differences of the Corded Ware males and the Early Bronze Age are either differences in amount of physical demand of the generally similar sedentary activities of the Corded Ware males or differences in proportion of the mobile and sedentary subsistence activities. Moreover, the biomechanical analysis has been designed without respect to subgroup differences such as differences associated with age and social status within female and male groups. Therefore, we can also expect that part of behavioral variability between the Late Eneolithic and Early Bronze Age may be obscured mainly because of the small sample size available for this analysis.

The only exception from the above conclusion is the Wieselburger sample. Both females and males exhibit reduced values of tibial length and females show decrease of tibial midshaft cross-sectional parameters in comparison with the Late Eneolithic and the rest of Bronze Age groups. These results confirm our previous conclusion based on the femoral midshaft cross-sections. The Wieselburger females are significantly different from the Late Eneolithic and Early Bronze Age groups, even though there is a significant decrease of some of the tibial midshaft parameters among the Wieselburger males. However, the Wieselburger sample does not show changes of pattern of mobility as indicated by the femoral and tibial index of mobility but the sample exhibits significant reduction in overall size and overall bending resistance. Since the reduction also affects tibial biomechanical length (i.e., longitudinal parameter highly correlated with stature) we could expect that behavioral adaptation produced different impacts of stress onto skeletal parts of the Wieselburger sample. Interesting point is that such a decrease is not correlated with all of the Early Bronze Age groups but only with the Wieselburger.

Given the fact that the Late Eneolithic and Early Bronze Age groups (except Wieselburger) exhibit similar patterns of biomechanical robusticity and bending/torsional resistance and only the Wieselburger sample is significantly different in several biomechanical parameters, we suggest that the transition from the Late Eneolithic to the Early Bronze Age did not bring unidirectional (diachronic) change of mechanical loading but the mechanical environment has been affected by behavioral processes (i.e., increase of social hierarchization, subsistence specialization, etc.) operating during the Late Eneolithic and Early Bronze Age as a mosaic across time and between/within cultures.

5. Conclusion

The biomechanical analysis of the tibial midshaft reveals no substantial differences in the tibial cross-sectional parameters of mechanical robusticity between the Late Eneolithic and Early Bronze Age with respect to mobility differences. Therefore, we can conclude that if some differences of mobility and/or subsistence strategy between the Late Eneolithic and Early Bronze Age existed, those activities did not produce significantly distinct patterns of mechanical loading on the tibial midshaft. The conclusion is well supported by the analysis of the Corded Ware females, who are similar in bending and torsional robusticity compared to the Early Bronze Age groups. Although some of the tibial midshaft cross-sectional parameters increase in the Corded Ware male sample, we expect that the increase is affected either by stochastic variation or by different amount of physical demand of generally similar pattern of subsistence strategy of the Late Eneolithic and Early Bronze Age. The only exception to the above conclusion is the decrease of the tibial midshaft parameters of the Wieselburger sample, which indicates overall reduction of size and bending resistance of the tibiae. We supposed that behavioral processes, which affected the tibial midshaft biology operated as a mosaic across time and between/within cultures during the Late Eneolithic and Early Bronze Age.

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