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Foot binding in a Ming Dynasty cemetery near Xi'an, China

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Keywords

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Abstract

This paper describes the morphology of the feet of a population of elite women from the Ming dynasty (1368-1644 CE) in Shaanxi province. This is a social stratum, time, and place in which foot binding was practiced. Among a group of 31 skeletons exhumed from the cemetery, eight were women with well-preserved foot bones. Macroscopic examination revealed that half these women (4/8) had clearly altered foot bones: the metatarsal bones, and the few observable phalanges, were gracile and small, while the tarsal bones exhibited a slight reduction in size but no dramatic change in morphology. The other half of the women (4/8) had apparently unmodified metatarsal bones. T-tests comparing linear measurements of the foot bones between the two groups revealed that metatarsal bones were the most affected by binding, and among the tarsal bones, the talar trochlea and calcaneal dimensions were most impacted. This small group of skeletons reveals that some elite women in Shaanxi apparently still did not practice foot binding in the late Ming dynasty, or practiced a much milder form of foot binding, and that there was considerable variation even among those who did practice it.

Introduction

Chinese foot binding is a form of body modification, well known today around the world, and widely discussed as a historical form of gendered violence and control of women's bodies (Stone, 2012). The origins of foot binding are uncertain, and our understanding of them relies on literary sources and legend, but it is generally accepted that the practice existed by the Northern Song dynasty at the latest (960-1127 CE) (Drucker, 2007; Levy, 1992). Foot binding began with the upper classes, eventually spreading through all strata of society and across all of China; it was probably widely practiced by the time of the Ming dynasty (1368-1644 CE), and was certainly widespread by the time of the Qing dynasty (1644-1911 CE) (Levy, 1992; Wang, 2000). By the Republican period (1912-1949 CE), supporters of modernization pushed to have foot binding banned, and began a campaign to change popular opinion about the practice. Binding steeply declined, and was eradicated completely after the Chinese Communist Party took power in 1949 (Gamble, 1943; Gerry, 1996; Ko, 2005; Levy, 1992; Wang, 2000). After nearly 1000 years and countless lives affected, foot binding is now almost beyond the reach of living memory.

Over this enormous stretch of time and space, the prevalence and method of foot binding changed to reflect fashions and values, including shifting attitudes towards women's roles in society, the nature of chastity, the desirability or danger of hedonism, etc. (Ko, 2005; Wang, 2000). By the Ming dynasty, bound feet had come to represent not only the ideal of womanhood and a form of obligatory bodily adornment among certain classes, but the Chinese empire and Han ethnic identity itself. Within this widespread practice, vast differences existed among local customs, such that a single comprehensive narrative of foot binding is nearly impossible to produce (Ko, 1997).

Beyond historical texts and objects such as shoes made for bound feet, the skeletal remains of women with bound feet are a critical source of data on the history, impact, and meaning of this practice in specific times and places. Skeletal remains pick up where archaeological and historical data leave off, giving us a window into the embodied experiences of women whose feet were bound, and revealing how their social lives were inscribed in their skeletons (Agarwal, 2016; Stone, 2012). To that end, this paper presents the skeletal evidence for foot binding from a Ming Dynasty cemetery at the site of Yangguanzhai, near the modern city of Xi'an, in central China's Shaanxi province.

Chinese foot binding

The exact form of foot binding was not uniform across time and space. In the early centuries of its practice, the intent of binding was to make the foot narrower and pointed; only later did it take on the arched shape seen in the latter days of the practice (Wang, 2000). The ideal size was said to be three "inches" (*cun*, a Chinese unit of measure), though the size of a standard inch also changed through time. In general terms, the shrinking and reshaping of the foot was accomplished by beginning to bind a girl's foot in childhood.

In historically documented cases, binding was usually begun between the ages of 5 and 7. At one year after birth, the female foot is approximately half its adult size, but it does not reach mature size until age 14. Furthermore, epiphyseal fusion in foot bones does not commence until after 10 years of age in females (the calcaneus begins fusion at 10-12 years, the heads of the second through fifth metatarsals at 11-13 years, etc.) (Scheuer and Black, 2004). Therefore, binding the feet in childhood, particularly before the age of 10, curtailed a significant amount of growth and impacted the morphology of the foot bones.

The binding was performed either by a female relative or by a professional foot binder. In the later form of the practice, the second through fifth toes were folded under the sole of the foot, and the front of the foot brought as close to the heel as possible, to increase the height of the arch and shorten the length of the foot. The binding accomplished these changes by inhibiting the growth of the bones, altering the ligaments and tendons, and changing the angles of joints, and not by breaking the bones, as is sometimes claimed (Drucker, 2007).

Long bandages were secured around the foot and then the entire foot was covered with a sock and a shoe, often elaborately embroidered. The bandages had to be frequently changed and the foot washed and rebound for the rest of the woman's life (Wang, 2000). The alterations to the foot also profoundly altered women's gaits and made walking difficult and painful. Despite this, when the practice reached its peak, even peasant and servant women, who were required to do agricultural and household labor, had their feet bound, though only in regions where dry-field rather than wet paddy agriculture was practiced, where feet could be left perpetually covered (Blake, 2008; Drucker, 2007; Wang, 2000). No reliable data are available for the exact rate of foot binding, though it is known to have varied by locale and social status, and reached the height of its popularity in the nineteenth century (Qin et al., 2015; Wang, 2000). The practice was almost exclusively limited to the Han people, the ethnic majority of China (Blake, 2008; Ko, 1997; Levy, 1992; Wang, 2000).

Historical sources, while containing abundant references to foot binding, are not adequate for reconstructing the variations in the practice through time and space. Many treatises, poems, novels, and essays mention the practice, usually praising the beauty of footbound women (Drucker, 2007; Peng, 2013). Most descriptions of the practice, however, rely on metaphor, innuendo, and poetic imagery (feet are described as "slender," "pointed," "bowed," shaped like lotuses or water chestnuts, etc.) (Ko, 2005; Levy, 1992). Explicit descriptions of foot binding became available beginning in the 19th century, when anti-foot binding crusaders, including both Chinese people and foreigners such as missionaries, set about photographing and documenting the phenomenon. Titillating souvenirs such as bound-foot women's shoes, photographs of prostitutes exposing their bound feet, and even, disturbingly, preserved feet themselves were brought back to the West by sailors and other travelers and became part of museum collections (Reznikov et al., 2017). In the 20th century, first-hand accounts by footbound women themselves were also published (Levy, 1992).

Women living with bound feet today number in the hundreds, virtually all over the age of 80 and many over the age of 90. Podiatrists, radiologists, and public health experts have taken on the task of documenting the morphological, biomechanical, and health consequences of foot binding in living footbound women, sometimes with the hope of improving their medical care. X-ray studies (Guo, 2011; Howard and Pillinger, 2010; Richardson, 2009), foot print analysis (Reischl et al., 2008), and gait analysis (Gu et al., 2015; Zhang et al., 2015) have all been applied to these now-elderly women. The studies have found some common characteristics of extant bound feet:

- the calcaneus tends to have a more vertical orientation than in unbound feet (Howard and Pillinger, 2010; Reznikov et al., 2017; Richardson, 2009);
- all or most foot bones are reduced in size, some with dramatically altered morphology, especially the metatarsal bones and phalanges of rays 2 through 5 (Gu et al., 2015; Guo, 2011; Howard and Pillinger, 2010);
- arthropathies throughout the foot and ankle, and changes in the angles of articulations, are common (Guo, 2011; Ma et al., 2013);
- the pattern of weight bearing in the feet is shifted, with the heel bearing more weight and the toes no longer functioning in their normal capacity during standing or walking (Gu et al., 2015; Qin et al., 2015; Reischl et al., 2008; Reznikov et al., 2017);
- the ankle has less motion in the sagittal plane (Gu et al., 2015; Zhang et al., 2015);
- bone density is reduced in the foot, and some studies have found that bone density is reduced in other weight bearing parts of the skeleton as well, while other studies have not found this to be the case; the discrepancy is possibly due to lifelong differences in physical activity among

groups of footbound women (Cummings et al., 1997; Guo, 2011; Howard and Pillinger, 2010; Pan et al., 2013; Qin et al., 2015; Richardson, 2009);

- development of anisotropic microarchitecture of trabecular bone in the calcaneus is somewhat disrupted (Reznikov et al., 2017);
- and elderly women with bound feet experience falls that result in fractures more often than women without bound feet do, though working class rural women seem to have been somewhat protected from this effect by remaining active all their lives (Cummings et al., 1997; Qin et al., 2015; Richardson, 2009).

These studies have been performed on the last generation of women to have their feet bound, during the Republican period (1912-1949). To understand the method of foot binding and the experiences of footbound women from earlier periods, historical accounts are valuable, but archaeological evidence is also essential, as it contributes data on variations in technique, the antiquity of the process, and the individual experiences of footbound women. Unfortunately, published archaeological data on foot binding are scant. Some shoes for bound feet have been discovered in mortuary contexts (Stone, 2012), and detailed studies of such shoes have also been undertaken (Ko, 2001; Li, 2012). These studies have confirmed that an earlier form of foot binding was intended to make the foot smaller, while the foot remained straight. Shoes from the Southern Song dynasty (1127-1279) were much longer than those of later eras, and the desired shape was pointed but not arched (Gao, 1995; Wang, 2000; Zhu et al., 2017). A mummy of this era—a rare published example of human remains with bound feet—was buried with her shoes and foot wrappings, and had feet measuring 18 cm long (Li et al., 1990). Only in the Ming Dynasty did the extreme version of the "three-inch golden lotus" begin to be practiced, while the earlier style likely persisted for some time alongside it.

Studying the skeletal remains of footbound women can reveal not only the evolution of foot binding across time and space, which reflected changing aesthetics and moral values, but also the prevalence of the practice, and the impact binding had on the rest of women's bodies. Currently, only a small number of bioarchaeological studies have presented evidence for foot binding, all from the Ming and Qing dynasties in north China, including the modern-day provinces of Shanxi (Zhu et al., 2017), Shandong (Zhao et al., 2017), and Henan (Lee, 2012, current special issue). This paper presents new data from the remains of women from Ming dynasty Shaanxi province.

Materials and methods

The site of Yangguanzhai is a large middle Neolithic village of the Miaodigou and Banpo IV periods (4000-3000 BCE) immediately to the northwest of the modern city of Xi'an (Figure 1). It has been under excavation since 2004, and in 2015, a Miaodigou period cemetery was discovered near the residential area of the site. Intruding into the Neolithic burials were a number of Ming dynasty brick chamber tombs belonging to local elites, with inscriptions that date them to the middle sixteenth to early seventeenth centuries, and that identify a number of the tomb inhabitants as members of the Zhang family.

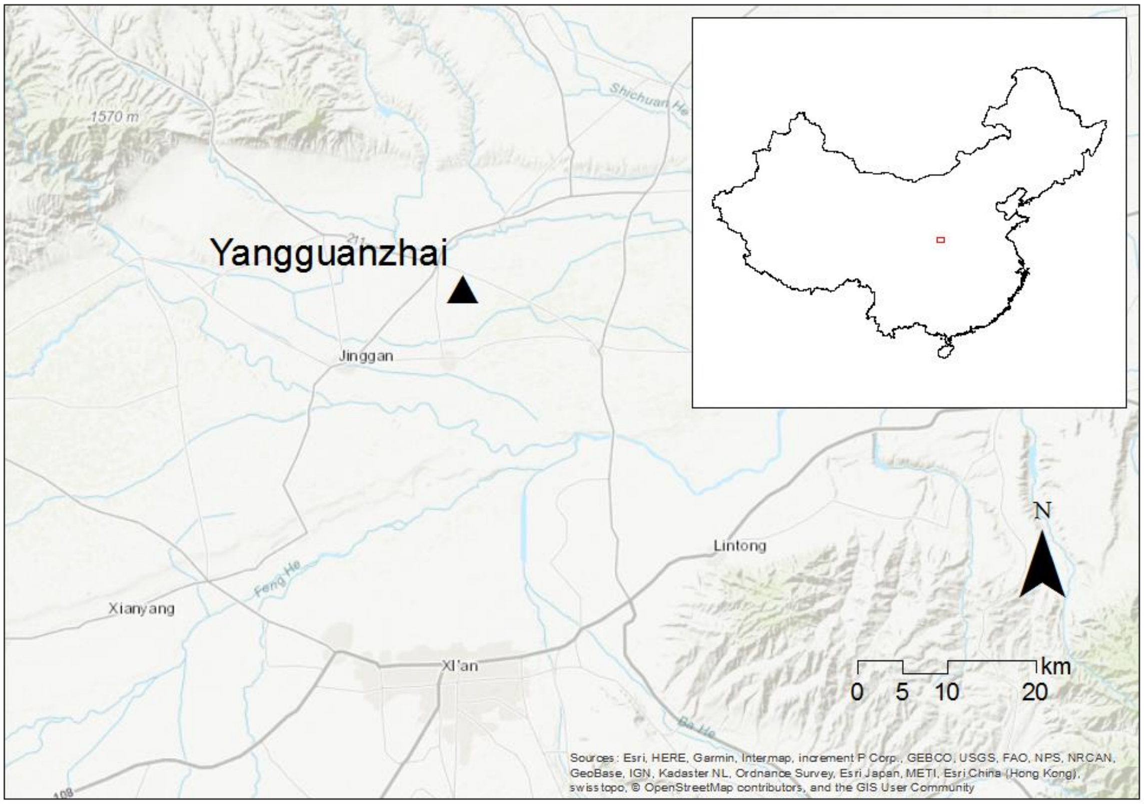

Figure 1 Location of the Yangguanzhai site

Archaeologists of the Shaanxi Archaeological Academy, directed by an author of the current paper (Yang), excavated human remains from 22 Ming tombs, totaling 31 skeletons. A bioarchaeological analysis was carried out by the first author (Berger). Age was estimated using multiple morphological methods (Brooks and Suchey, 1990; Buckberry and Chamberlain, 2002; Buikstra and Ubelaker, 1994; Iscan, 1991; Langley-Shirley and Jantz, 2010), and a final age-at-death range derived for each individual. Documented age at death is also available for some of these individuals, as their tombs contained inscriptions giving birth and death dates; the tomb inscriptions were transcribed and translated by the third author (Ye).

The 31 skeletons included 11 adult males, 14 adult females, two adults of indeterminate sex, and four subadults (Table 1). Six of the tombs were couples burials, containing a male and a female adult interred together, and two were triple burials, containing one male and two females. The bones were removed from the tombs in 2015 and stored at the Yangguanzhai field station. They are well preserved, with many small bones of the hands and feet recovered and cortical surfaces and epiphyses largely intact.

Table 1 Distribution of sexes among Yangguanzhai Ming burials

Male	Female	Indeterminate	Subadult	Total
11	14	2	4	31

All the preserved foot bones of the female skeletons were macroscopically observed and measured in the summers of 2016 and 2017 by Berger. It was not possible to do histological analysis or apply other imaging methods due to the bones' location at a rural field station and lack of ability to do destructive analysis. Linear measurements were taken on the femora, tibiae, tarsal bones, and metatarsal bones for all women with preserved foot bones. A one-tailed t-test was then used to compare all measurements between the four women whose feet were bound and the four women whose feet were possibly not bound. The test was conducted first on all bones combined, and then on left and right feet separately to account for possible asymmetry. Some of the tests may not have reached statistical significance due to small sample sizes of $N<5$.

Results

Estimated or recorded age, foot binding status, and relevant pathological lesions of all female individuals are recorded in Table 2. Eight adult females had well-preserved metatarsal bones, while the other six had no foot bones or only fragmentary foot bones preserved. Four of eight women (50%) with foot bones from this assemblage clearly had bound feet based on abnormal morphology of the tarsal bones, metatarsal bones, and phalanges. The other four women presented without obvious foot bone modification, suggesting their feet may not have been bound, or may have been bound in a different way. This ambiguity is exacerbated by the fact that not all foot bones were recovered from each individual. For the remaining six women, no complete metatarsal bones were observable, and the few observable tarsal bones were not clearly altered, though binding could not be ruled out.

Table 2 Female skeletons from Yangguanzhai Ming tombs. M is the Chinese designation for a tomb feature (*muzang*); E indicates east (position within the tomb), W indicates west, and M indicates middle. Asterisk indicates age at death was recorded in tomb inscription.

	Individual	Age at death	Other observed pathological lesions
Bound			
	M57E	37-46	Foot bones: **L** talus, calcaneus, cuboid, MT2, MT3 (shaft only), MT4, MT5; **R** calcaneus, cuboid, MT4. Talar head slightly flattened, medial subtalar facet quite small. Calcaneal tuberosities normal, medial talar facets narrowed, facet for cuboid also small. Cuboids appear narrowed medio-laterally, facet for MT4 very small, facet for calcaneus quite narrow. Other lesions: healing periosteal new bone on femora, linear enamel hypoplasias (LEH) on canine teeth.
	M59W	37-46	Foot bones: **L** talus, calcaneus, MT1, MT2; **R** talus, calcaneus, MT1-5. Talar heads flattened, medial talar facets of calcanei elongated. Other lesions: very mild osteophytes on lumbar vertebrae, very mild lipping on joint surfaces of hips, knees. Healing periosteal new bone on femora and tibiae, left fibula. LEH on canines.
	M80W	23-71	Foot bones: **L** talus, calcaneus, cuboid, navicular, MT3-5; **R** talus, calcaneus, navicular, cuboid, medial cuneiform, MT1-5. Other lesions: very well-healed periosteal new bone on tibiae, femora. Mild lipping on distal femora, acetabula. Moderate to severe osteophytes on lumbar spine, mild osteophytes in thoracic spine.
	M86E	25-50	Foot bones: **L** talus, calcaneus, navicular, cuboid, MT1, MT3-5; **R** talus, calcaneus, navicular, medial cuneiform, MT1-5. Five proximal foot phalanges present, 2-5 are very small and thin. Other lesions: very mild osteophytes in lumbar vertebrae. Very well-healed periosteal bone on tibiae and femora. Faint lipping on distal femora and proximal tibiae. LEH on the mandibular canines.
Unbound			
	M53W	60*	Foot bones: **L** talus, calcaneus, navicular, cuboid, MT1-5; **R** talus, calcaneus, navicular, cuboid, MT1-5. Other lesions: advanced osteoarthritis in knees (incl. grooving, proliferation, lipping, porosity), mild lipping in hips, elbows, shoulders (left shoulder was chronically anteriorly dislocated with pseudojoint formation on scapula and humeral head erosion). T12-L1 block vertebrae. Severe osteophytes in lumbar and thoracic vertebrae, lipping in metacarpal heads. Healing periosteal bone on tibiae and femora. LEH on a canine tooth.
	M53E	33*	Foot bones: **L** navicular, cuboid, MT1-3, MT5; **R** talus, calcaneus, navicular, cuboid, 1st cuneiform, MT1-5. All appear normal. Other lesions: healing periosteal bone on tibiae and femora, very mild lipping only on right distal tibia.

	M57W	24-31	Foot bones: **L** talus, navicular, medial and lateral cuneiforms, MT1-5; **R** talus, calcaneus, cuboid, MT1, MT4, MT5. Tarsal and metatarsal bones appear normal, but one altered proximal foot phalanx is present. Other lesions: healing periosteal bone on tibiae, femora. Moderate to severe osteophytes in lumbar spine, mild to moderate osteophytes in thoracic spine. L2 compression fracture with wedging. Osteoarthritis on articular facets of thoracic vertebrae, T3 and T4 have ankylosed at the articular facets. Barely discernible lipping in distal femora, acetabula.
	M82	26-71	Foot bones: **L** calcaneus, navicular, MT1-3; **R** talus, calcaneus, cuboid. Medial talar facets of calcanei are quite round, right cuboid (broken), right talus, left navicular (broken) appear normal. Other lesions: Very faint lipping in acetabula, mild to moderate osteophytes in thoracic vertebrae, mild osteophytes in lumbar vertebrae. Mild lipping on distal femora, proximal tibiae. Well-healed periosteal new bone on tibiae.
Foot bones absent or fragmentary			
	M54W	36*	No foot bones present. LEH on canines.
	M77	37-71	Foot bones: **R** MT2 (partial). Other lesions: mild lipping in acetabula. L4 and L5 vertebrae exhibit severe osteophytes, L4 has spondylolysis without reattachment (both segments present), OA in articular facets. Mild to moderate lipping and proliferative bone on articular surface of left patella. LEH on canines.
	M55M	80*	Foot bones: **L** calcaneus, appears normal. Other lesions: osteophytes (mild to moderate) on thoracic vertebrae (lumbar absent). Very mild lipping in acetabulum (only left present), mild lipping and osteophytes on distal femora (tibiae absent).
	M60W	Too fragmentary to estimate	Foot bones: **L** talus, calcaneus (partial), medial cuneiform; **R** talus, cuboid (partial); fragment of a MT1 shaft. Cuneiform and cuboid appear slightly narrowed, medial talar facet of calcaneus possibly elongated. Other lesions: slight lipping on talar and calcaneal articular surfaces, healing periosteal new bone on all leg bones, mild lipping on hips and knees.
	M61W	Fragmentary	No foot bones present. LEH on canines, two premolars, one molar.
	No num.	Fragmentary	No foot bones present.

Individuals M57E, M59W, M80W, and M86E have clearly altered metatarsals bones (Figure 2). In these individuals, the metatarsals, especially the second through fifth, are shortened in length and have very thin, gracile shafts and small distal heads. The proximal ends of the bones are less dramatically altered and appear bulbous next to the small shafts. Individuals M53W, M53E, M57W, and M82 had metatarsal bones with apparently normal morphology.

The tarsal bones have undergone much more subtle alterations (Figure 3). The calcanei appear only slightly shortened in length, but are not clearly abnormal in shape. The tali are similarly subtly altered: they have an almost normal shape, but are slightly shortened antero-posteriorly, so they appear squat. The joint surfaces, more than the bone dimensions, seem the most impacted. None of the other observed tarsal bones had apparently abnormal morphology.

Unfortunately, only two of the female skeletons had preserved foot phalanges. One individual had five proximal phalanges, all but the first not identifiable as to ray (Figure 4). Another individual had only one proximal phalanx, also not identifiable as to ray, but almost certainly not a first phalanx. All the observable phalanges except the single first phalanx had clearly altered morphology, being very short and with an extremely thin shaft and bulbous epiphyses. They are identifiable as proximal phalanges by their concave proximal articular surfaces.

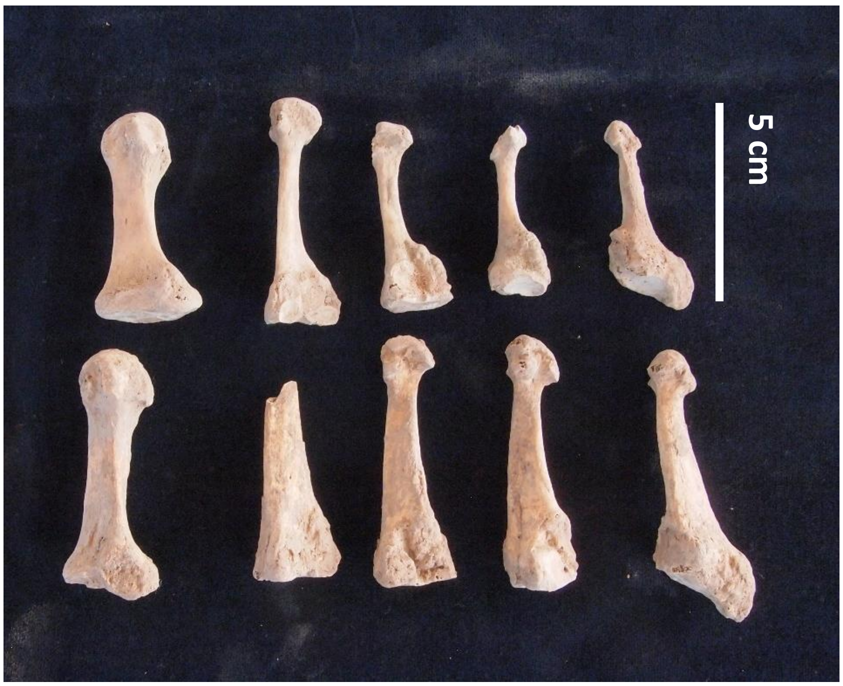

Figure 2 Range of variation among the metatarsal bones of Yangguanzhai female skeletons: right metatarsal bones of M59W (top) and M53W (bottom), lateral view (fifth metatarsals plantar view).

Figure 3 Range of variation among the joint surfaces of tarsal bones of Yangguanzhai female skeletons: left calcaneus of M55M (left) and M57E (right), anterior-superior view.

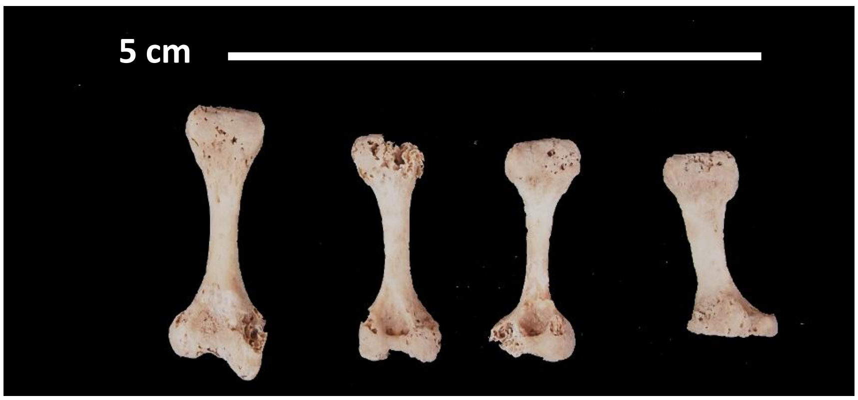

Figure 4 Proximal foot phalanges of M86E, except the first proximal phalanx; plantar view, distal is up. Porous appearance of the epiphyses is from postmortem damage.

Measurements of the foot bones are summarized in Table 3, and the results of significance tests in Table 4. In this analysis, the women were divided into bound and unbound groups based on the morphology of their metatarsal bones. The t-tests revealed that metatarsal bones, calcanei, and tali were the most affected by binding. The length of the talar trochlea was impacted, though not the width of the trochlea or the body height of the talus. None of the measurements taken on the cuboid or navicular differed significantly between the groups. All metatarsal bones showed significant differences in their articular lengths and midshaft heights, though the more lateral metatarsal bones were more affected by binding. This makes the dimensions of the first and second metatarsal bones less useful for identifying which feet were bound. For instance, even though M53E appears not to have had bound feet, and the third through fifth metatarsal bones are clearly larger than those from bound feet, the first and second metatarsal bones of M53E are relatively small and fall within the range of the metatarsal bones from bound feet.

Table 3 Mean, N, and standard deviation for measurements taken from the eight female individuals with preserved metatarsal bones

	Bound						Unbound					
	Right			Left			Right			Left		
	Mean	N	SD	Mean	N	SD	Mean	N	SD	Mean	N	SD
Femur antero-posterior diameter at midshaft	22.7	4.0	1.0	23.3	4.0	0.6	25.4	4.0	2.0	25.5	4.0	2.3
Femur medio-lateral diameter at midshaft	24.1	4.0	1.7	25.0	4.0	1.6	26.5	4.0	1.3	26.3	4.0	1.2
Femoral head maximum diameter	42.5	4.0	3.3	42.2	4.0	2.5	45.3	4.0	6.3	42.1	4.0	2.1
Femoral distal epiphyseal breadth	73.2	4.0	3.2	72.1	4.0	2.6	73.3	4.0	3.6	72.8	4.0	3.3
Tibia distal epiphyseal breadth	43.3	3	3.1	50.7	4	11.2	45.0	4	4.8	46.4	4	3.7
Tibia midshaft maximum diameter	24.9	4	0.8	24.6	4	1.6	26.6	4	0.5	26.5	4	1.2
Platycnemic index*	71.2	4	5.4	74.7	4	2.8	70.2	4	7.0	70.5	4	7.8
Calcaneus maximum length	66.9	3	0.6	68.3	4	1.1	71.0	4	3.3	72.4	1	0.0
Calcaneus posterior length	48.9	4	2.5	49.0	4	1.8	49.8	4	2.7	48.0	1	0.0
Calcaneus load arm width	35.7	4	1.7	34.4	2	1.6	38.8	4	1.5	38.9	3	0.9

Calcaneus height	41.1	4	0.9	45.8	4	2.0	43.0	2	0.1	47.6	4	3.2
Calcaneus load arm length	40.6	4	1.1	41.1	4	0.9	43.6	4	2.0	44.9	2	2.0
Talus body height	21.8	3	1.8	23.9	3	1.0	22.0	3	0.4	23.3	2	0.6
Talus maximum length of trochlea	26.9	3	1.2	28.1	4	1.1	29.7	3	0.6	29.6	2	0.0
Talus maximum width of trochlea	25.2	3	2.3	27.1	3	1.5	27.4	3	2.4	26.6	2	2.6
Cuboid inner length	30.5	3	1.3	29.7	3	1.6	30.2	4	3.1	27.7	2	1.2
Cuboid outer length	17.2	3	1.1	16.0	3	1.0	17.8	4	0.9	17.0	2	1.2
Navicular thickness	16.4	2	1.4	16.2	1	0.0	15.4	1	0.0	16.9	3	0.5
MT1 maximum length	53.7	3	0.7	54.2	2	0.7	56.5	3	3.3	59.2	4	0.3
MT1 articular length	50.9	3	0.6	50.5	2	0.4	52.7	3	3.0	53.9	4	2.1
MT1 midshaft height	9.6	3	0.4	10.1	2	0.1	10.5	3	1.0	11.2	4	0.6
MT2 articular length	56.0	3	2.2	56.6	1	0.0	60.0	1	0.0	63.7	4	2.8
MT2 midshaft height	6.7	3	0.6	5.8	2	0.4	7.8	2	1.0	7.6	4	0.7
MT3 articular length	50.6	3	2.4	56.6	1	0.0	58.4	2	0.5	60.8	4	2.2
MT3 midshaft height	5.4	3	0.4	6.2	3	0.4	6.8	3	1.7	7.6	3	0.8
MT4 articular length	48.7	2	2.4	47.5	2	0.9	58.1	3	0.7	54.6	1	0.0
MT4 midshaft height	5.2	4	0.9	5.4	3	0.6	7.4	3	0.9	6.1	1	0.0
MT5 articular length	45.6	3	3.3	48.7	2	0.5	54.3	3	1.5	55.0	3	2.3
MT5 midshaft height	6.8	3	0.9	6.2	3	1.4	8.6	3	1.2	9.2	3	0.9

*The platycnemic index is the ratio of the anteroposterior diameter of the tibia divided by its lateral diameter, multiplied by 100.

Table 4 One-tailed p-values for two-sample t-test assuming unequal variance. **=significant at the p<0.05 level, *=significant at the p<0.10 level. Italicized measures are those that exhibited significant differences between the bound and unbound groups on left, right, or both.

Measure	Bound vs. unbound	Bound vs. unbound R	Bound vs. unbound L
Femur antero-posterior diameter at midshaft	0.011**	0.051*	0.105
Femur medio-lateral diameter at midshaft	0.021**	0.054*	0.151
Femoral head maximum diameter	0.269	0.262	0.480
Femoral distal epiphyseal breadth	0.403	0.484	0.384
Tibia distal epiphyseal breadth	0.337	0.327	0.282
Tibia midshaft maximum diameter	0.005**	0.014**	0.072*
Platycnemic index	0.221	0.426	0.211
Calcaneus maximum length	0.034**	0.062*	--
Calcaneus posterior length	0.383	0.348	--
Calcaneus load arm width	0.002**	0.027**	0.115
Calcaneus height	0.095*	0.017**	0.220
Calcaneus load arm length	0.009**	0.037**	0.159
Talus body height	0.367	0.444	0.291
Talus maximum length of trochlea	0.003**	0.029**	0.050*
Talus maximum width of trochlea	0.287	0.197	0.442
Cuboid inner length	0.309	0.435	0.160
Cuboid outer length	0.114	0.273	0.273
Navicular thickness	0.414	--	--
MT1 maximum length	0.003**	0.175	0.046**
MT1 articular length	0.024**	0.245	0.029**
MT1 midshaft height	0.011**	0.152	0.018**
MT2 articular length	0.003**	--	--
MT2 midshaft height	0.015**	0.250	0.029**
MT3 articular length	0.007**	0.008**	--
MT3 midshaft height	0.040**	0.198	0.046**
MT4 articular length	0.000**	0.082*	--
MT4 midshaft height	0.018**	0.026**	--
MT5 articular length	0.001**	0.021**	0.034**
MT5 midshaft height	0.004**	0.087*	0.040**

The measurements confirm the observations made by macroscopic examination: the metatarsal bone dimensions are significantly different between the groups, and the distributions of their measurements do not overlap (Figure 5). In contrast, the overall dimensions of the tarsal bones mostly do not differ significantly, and their distributions largely do overlap (Figure 6). Finally, the joint surface dimensions of the tarsal bones mostly do show significant differences; however, their distributions still overlap (Figure 7). Dimensions of both overall tarsal bone shape and tarsal joint surfaces are quite variable.

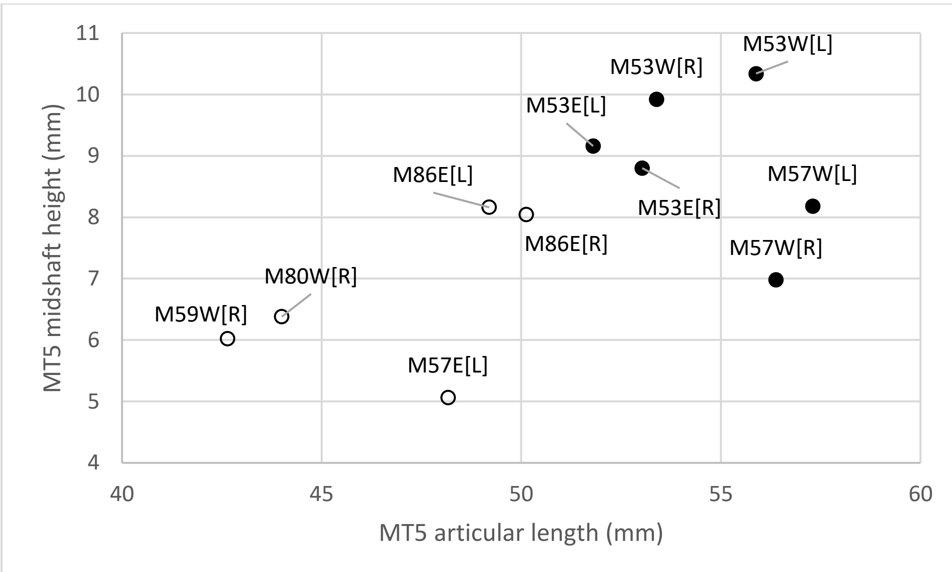

Figure 5 Scatterplot showing non-overlapping fifth metatarsal dimensions between bound (open circles) and unbound feet (filled circles)

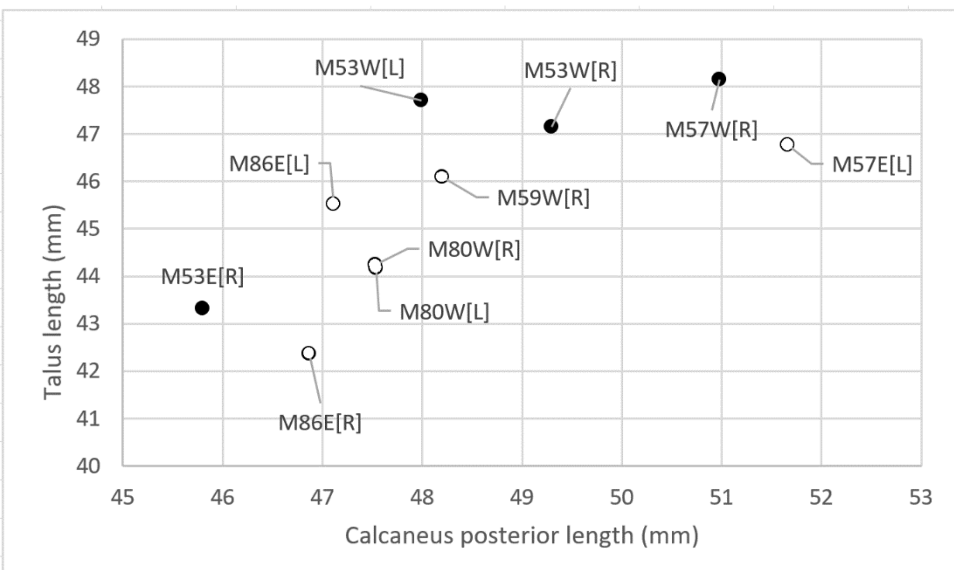

Figure 6 Scatterplot showing overlapping tarsal bone dimensions between bound (open circles) and unbound feet (filled circles)

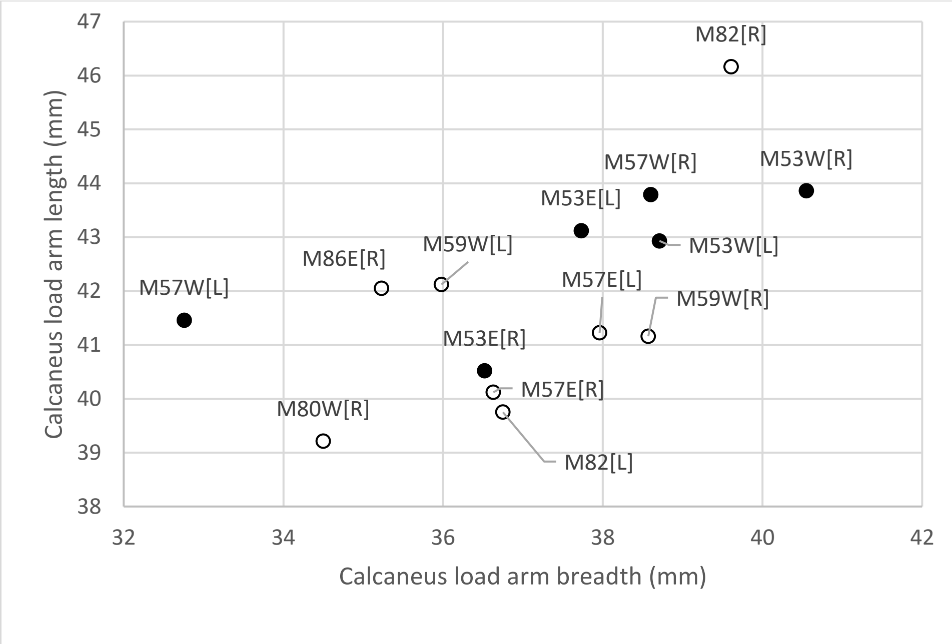

Figure 7 Scatterplot showing overlapping tarsal bone joint surface dimensions between bound (open circles) and unbound feet (filled circles)

Discussion

Among the eight individuals whose foot bones could be examined, the calcaneus load arm, talar trochlea, and metatarsal bones were particularly affected by binding. This is consistent with what is known of the foot binding process. In the arched form of binding, the orientation of the calcaneus was made more vertical, which would change the direction of weight bearing by both the calcaneus and the talus (Guo, 2011). The first metatarsal bone was not repositioned, though its weightbearing during walking was increased in bound feet (Gu et al., 2015). The other four metatarsal bones were folded under the plantar surface of the foot and bound in place, which significantly stunted their growth and altered their function.

None of the epiphyseal dimensions of the tibiae or femora are different between the groups, but both bones show a reduction in shaft size in the group with bound feet. This accords with leg atrophy reported or postulated in some other studies of footbound women (Pan et al., 2013; Zhang et al., 2015). The platycnemic index (the ratio of the anteroposterior diameter to lateral diameter of the tibia at midshaft) does not differ between the groups, indicating that the cross-sectional geometry of the shaft may not be affected. The difference in gracility of the tibiae and femora shafts possibly reflecting different levels of activity between the groups, though clearly the footbound women were active enough for joint surfaces in the legs to form normally and for epiphyses to reach normal dimensions.

Despite the limited sample size of this study, among the four women with clearly altered metatarsal bones, a range of morphological variation was still present. Variation in the morphology of bound feet can be explained by the many factors that influenced the process, including the skill and diligence of the foot binder, and the adherence of each woman to the initial foot binding regimen in childhood.

An important question to ask of this assemblage is whether the morphological differences between the women's foot bones represent the differences between bound and unbound feet, or represent different styles of binding. When individuals are sorted according to their metatarsal bone morphology, as in the t-tests above, tarsal bones also differ significantly between the groups. It is not possible to rule out a different form of foot binding for the women in the larger foot category, but it would have to be a method that did not significantly alter the morphology of the foot bones. One of the individuals with apparently normal metatarsal bones, M57W, also had one clearly altered foot phalanx, though it is possible this bone was commingled and in fact belonged another woman, for instance M57E, who was buried in the same tomb and had clearly altered metatarsal bones.

By the late Ming dynasty, two distinct styles of foot binding were practiced in China. First was the earlier form of narrow, pointed, but not arched foot, which likely persisted throughout the Ming. Second was the form that arose sometime during the Ming and would eventually come to dominate, namely, the heel-weight-bearing type, in which the toes were folded under and the height of the arch drastically increased, to reduce the overall size of the foot. This relied on the invention of the high-heeled shoe to make walking possible. (A final form, supposedly practiced in Fujian, involved bending the toes upward, sometimes at a 90-degree angle [Levy, 1992; Qin et al., 2015; Zhu et al., 2017], though this form has not been well-documented.) The Yangguanzhai cases of bound feet may have been of either the narrow or the arched type, though the similarity of the metatarsal bones to those of documented cases from the Qing dynasty (see below) suggests the arched form. It is also possible that the "bound" and "unbound" feet at Yangguanzhai may in fact represent the two different types of binding. Further research on skeletal remains from times and places where foot binding practices were more thoroughly documented, or where shoes are available for comparison, will be needed to understand the differences in foot bone morphology across different types of binding.

One serious limitation to this study is the absence of many foot bones, particularly phalanges. The burials do not appear to be secondary, but some are clearly disturbed, either by the later interment of other tomb occupants or by post-depositional forces such as water intrusion. Tomb inscriptions from Yangguanzhai reveal that there was sometimes an interval—from several months to several decades—between the date of a woman's death and initial interment, and the date of her final interment when the tomb was reopened to inter her husband. Length of this burial interval is not correlated with number of foot bones preserved, but disturbance could still explain some of the lack of preservation. The relative absence of phalanges could also be due to failure of recovery of small bones (Stone, 2012), or to the possibility that the toes of footbound women were lost in life due to necrosis. However, the latter phenomenon, while often described by contemporary writers, is not historically well-documented, and would not account for the near complete absence of both hand and foot phalanges for both male and female individuals in this cemetery.

Finally, the foot bones of both the bound and the unbound feet of the Yangguanzhai women are smaller than those of modern people, according to a study of modern foot bone growth, based on a 20th-century sample of European and African Americans. The average maximum length of the calcanei and the average lengths of the second through fourth metatarsals of both groups from Yangguanzhai fall within the range of modern individuals of 10-15 years of age (Passalacqua, 2011; Passalacqua et al., 2012). The smaller size of the Chinese women's feet could be due to population differences in foot bone size, secular change, or environmental factors that impacted growth. What is most interesting, however, is that the lengths of the metatarsals of the bound feet were as large as those of American children who were at least 10 years of age. This could indicate that the feet of women at Yangguanzhai were not bound until closer to 10 years of age, not at 5-7 years of age as they would have been in the nineteenth century. It could also indicate that even when feet were bound earlier in childhood, the binding did not entirely arrest the growth process, and by the end of the growth period, the bones had attained the length of those of an older child. Again, the precise impact of binding on growth will have to await osteological studies of bound feet from periods in which the age of binding was more thoroughly documented.

Comparative cases

Only a few other osteological cases of foot binding have been reported (Hou, 2013; Lee, 2012; Zhao et al., 2017; Zhu et al., 2017), all of which describe cases of foot binding from different parts of north China in the Ming and Qing dynasties. These studies reveal clear differences in how foot binding manifested in women's skeletons, though all have found that the greatest morphological changes occurred in the metatarsal bones.

At the cemetery of Yuci in Shanxi Province, anthropologists observed 18 female skeletons, primarily commoners of the Qing dynasty, all of which showed deformities in their feet presumably resulting from foot binding (Zhu et al., 2017). The changes were characterized by overall smaller size of foot bones, and developmental and degenerative changes to the joint surfaces. The metatarsal bones in these individuals closely resemble those from Yangguanzhai, with reduced length and shaft diameter. The investigators also observed degenerative changes in the tarsometatarsal joints. The cuboid bone was markedly reduced in size, especially the medial articular surface. Only a few medial cuneiform and navicular tarsal bones were observable, and showed slight reductions in overall size. The talus bones were smaller overall but were not significantly altered in shape, similar to the cases from Yangguanzhai. The clearest distinction between the Yangguanzhai and Yuci skeletons is in the calcaneus: the Yangguanzhai skeletons had calcanei that were somewhat reduced in overall size and joint surface size, but did not have drastically altered shapes, while the Yuci skeletons had calcanei with clearly altered shapes, namely, the middle of the calcanei were narrowed relative to the proximal and distal ends. Only three individuals had observable phalanges, and these were reduced in size, as well as having the orientations of their articular surfaces altered. The investigators concluded that the clearest changes were in the metatarsal bones. Similar to Yangguanzhai, no individual had all foot bones present, so no complete foot skeleton could be reconstructed.

Guo (2011) used x-ray and CT images to compare bone dimensions of bound and unbound feet of living women in Yunnan. Though this study concerned living women and not an archaeological group, it still provides comparative measurements of bone dimensions. The measurements of the metatarsal bone lengths and widths are similar to those from Yangguanzhai, though the Yangguanzhai bones are slightly smaller. This could be due to differences in foot binding methods, to secular change, or to systematic differences between dry bone measurements and measurements from x-rays.

See also the current special issue for more recent osteological studies on foot binding.

The women at Yangguanzhai, when compared with cases from other sites, have equally extreme modification of the metatarsal bones but less extreme modification of the tarsal bones, especially the calcanei. This could be due to local variations in the practice, or to change in the practice through time.

In terms of changes elsewhere in the skeleton, the Yangguanzhai women did exhibit more gracile tibiae and femora, possibly indicating some atrophy or reduced activity during growth. They did not exhibit fractures that might have resulted from falls. Several women exhibited striated periosteal new bone on the leg bones, which was healing (in the process of being resorbed), but this is also not uncommon in archaeological populations and cannot be attributed to having bound feet. Linear enamel hypoplasias (LEH) on anterior tooth crowns can indicate physiological stressors that interrupted ameloblast activity between the ages of 1 and 6 (Agarwal, 2016). More of the footbound women had LEH on the anterior dentition than the non-footbound women, but the difference is not statistically significant (likely because of the small sample size).

Some of the women at Yangguanzhai exhibited osteoarthritis (OA) of the limbs and spine, though it is not possible to attribute the progression of their OA specifically to their bound feet or altered gait. Of the women whose foot bones were present, the four with and the four without bound feet seemed to have equivalent degrees of development of OA, with the exception of one young adult woman without bound feet (M57W) who had severe osteoarthritis in the spine and a compression fracture of the second lumbar vertebra. In M53W, also one of the unbound group, the short plantar ligament (connecting the cuboid and calcaneus) was ossified, which can result from a range of arthropathies or injuries, and is not sufficient for a differential diagnosis. Though these pathological cases are anecdotal, they may indicate that there was a greater burden on the women without bound feet (or with less severely bound feet) of activity or domestic labor. These lesions may represent the embodied experiences of these women, in terms of both individual practices of body modification and also possibly of social standing and daily activities.

Conclusion

The Yangguanzhai foot binding cases provide a glimpse of the practice among a small group of elite women in late Ming dynasty Shaanxi. Only half the women whose foot bones were preserved appear to have had their feet bound, and among those with bound feet, the metatarsal bones and phalanges show the most modification, with tarsal bones less clearly modified than those from the Qing dynasty in other provinces.

The last living women with bound feet have provided much information to researchers regarding the practice of foot binding, including its effects on both their bodies and their social lives, though they only represent one brief period at the end of the practice. There are also many historical writings on foot binding, though most were produced by men. Bioarchaeological data on the remains of women with bound feet are critical for understanding the experiences of the women who underwent binding during the approximately ten centuries in which it was practiced. Examination of women's skeletal remains from contexts in which binding was practiced should include careful observation of foot bones, as well as comparison with excavated shoes where available. The current study illustrates how bioarchaeological evidence can contribute to our understanding of the variation in foot binding practices through time and space, and even within a single cemetery, which may not be reflected in the written record.

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