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Case study

A severe case of bilateral humerus varus deformity from the Middle Bronze age necropolis of Olmo di Nogara, Northeast Italy. The contribution of biomechanical analysis to paleopathological study

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ABSTRACT

Objective: To gain insights on possible impairment of a Middle Bronze Age individual with bilateral humerus varus buried with a sword in Northeastern Italy.
Materials: A skeleton of a 40–50-year-old male from Olmo di Nogara (Italy) compared to other males from the same necropolis and to Neolithic and Iron Age samples from Italy.
Methods: Macroscopic/X-rays analysis for pathological diagnosis and cross-sectional geometric analysis.
Results: Both humeri of the individual appear short with destruction of the humeral heads, showing severe osteoarthrosis and flattening of the scapular glenoid cavities. The individual showed appreciable humeral bilateral asymmetry; there is no evidence for sustained immobilization.
Conclusions: The pathological modifications suggest a diagnosis of bilateral humeral varism probably following an injury at birth. The individual's life was likely not significantly affected, as evidence suggests that he remained active and possibly used weapons.
Significance: Biomechanical analyses provided a useful tool to reconstruct the life of the subject within the community, showing that this individual's apparent upper limb abnormalities did not exempt him from a role as a warrior and highlighting the importance of the warrior identity in this Bronze Age society.
Limitations: The complex interaction between epiphyseal damage and shortening of the humerus makes it difficult to assess activity patterns. Only severe impairment leading to long-term immobilization can be excluded for this individual.
Suggestions for Further Research: Cross-sectional geometry may be used in other cases of humerus varus or bone dysplasia to investigate functional impairment.

1. Introduction

Individuals with skeletal abnormalities are usually excluded from the study of past activities, given that their bone structural adaptations and degeneration (e.g. enthesopathies, biomechanical properties) are expected to be unrepresentative of population-level habitual tasks or other socially relevant activities (e.g. military training). In addition, bone morphology, including the internal structure, may be altered by pathological conditions, rendering the application of standard methods difficult, and the results less indicative of activity. Nevertheless, individuals with possible impairment have interested bioarchaeologists for decades (Solecki, 1971; Trinkaus, 1983; Frayer et al., 1987; Dettwyler, 1991; Hawkey, 1998). Recently, significant methodological and theoretical advancements have led to a holistic perspective, aiming at gaining insights into social practices and norms from the analysis of potentially disabled individuals within their environmental and social contexts (Tilley, 2015; Tilley and Shrenk, 2018). It should be noted that not all dysplasias result in impairment, or even disability needing

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accommodation from family members or the larger group (Byrnes and Muller, 2017). Past people were quite resilient (Dettwyler, 1991), and assessing whether and how a disability affected the lives of individuals with skeletal dysplasias (and that of the people around them) can be enhanced by construction of an osteobiography (e.g. Tilley and Oxenham, 2011). Reconstructing individual behavior from skeletal remains is often challenging, and the answer to the main question – the actual occurrence of the impairment, and the extent to which such impairment constituted a disability – often remains unknown (e.g. Tilley, 2015). Although reconstructing individual activity levels may be impossible, due to the well-known variability in bone response to similar stimuli, certain approaches have aimed at assessing or excluding severe impairments during development (e.g. Sparacello et al., 2016; Mansukoski and Sparacello, 2018; Sparacello et al., 2023; Gilmour et al., 2019, 2022, 2023).

In this paper, we discuss a case of bilateral humerus varus, complicated by severe osteoarthrosis at the glenohumeral joint, in a Bronze Age skeleton buried with military paraphernalia. Besides contributing to the protohistoric documentation of this uncommon bone dysplasia, the osteobiography of this individual may enhance our understanding of the perception of this condition in Bronze Age societies.

2. Materials and methods

2.1. Materials

The Bronze Age cemetery at Olmo di Nogara (OdN) is dated to the Middle Bronze Age (ca. 1650–1200 BCE) and is located in the Tartaro valley near the modern town of Verona (Northeast Italy, Fig. 1). Excavations between 1987 and 1995, and in 2009, unearthed 525 tombs, 464 of which were simple inhumations and 61 were cremations in cinerary urns. The grave goods accompanying the deceased consisted mainly of bronze swords for men, and for women included ornaments such as bronze or amber pendants and bone combs (Salzani, 2005).

The burial in this study (individual OdN 410) consists of a primary deposition in a simple pit in which the skeleton lay supine with the upper and lower limbs extended (Fig. 2). Above the right scapula, five bronze hemispheric knobs were placed, whose function is still unclear. They may represent rivets of a leather helmet that was lost to decomposition. Below the right clavicle, an intact Sprockoff/1b Asenkofen-type bronze sword was placed. This type of sword dates the burial to the 13th century BCE (Salzani, 2005). The skeleton is well preserved and complete, allowing for an attribution to a male individual based on pelvic and cranial morphology (Buikstra and Ubelaker, 1994, Byers, 2002). Age at death was estimated to be around the fourth-fifth decade of life, based on changes of the pubic symphyseal surface (Katz and Suchey, 1986), morphology of the 4th rib sternal end, and dental wear (Brothwell, 1981). Remains are curated at the University of Pisa (Italy).

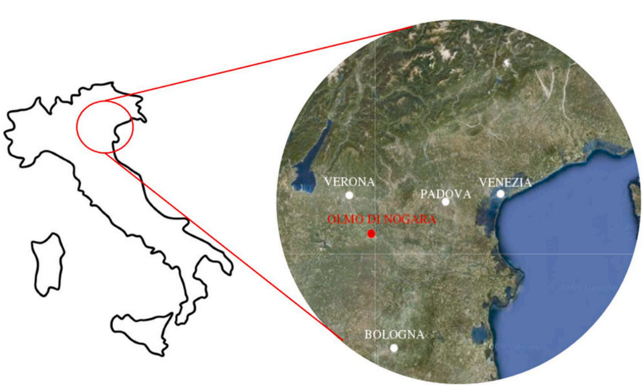

Fig. 1. Map of Western Italy showing the location of the necropolis of Olmo di Nogara on the right hand-bank of the riverbed in the Tartaro Valley, Veneto.

For the study of postcranial functional adaptations, we compared individual OdN 410 with a sample of 11 males (six buried with a sword, similar to individual OdN 410) from the same site and chronological phase based on accompanying grave goods. Additional comparative samples included series predating and following the Bronze Age, coming from different areas of the Italian peninsula. The 24 Neolithic males from Liguria (ca. 5300–4000 BCE) (Sparacello et al., 2019, 2020) had a subsistence based on pastoralism, and showed biomechanical indicators of high mobility levels, and some evidence of unilateral use of the upper limb, possibly due to woodworking (Marchi et al., 2006; Sparacello and Marchi, 2008). For the Iron Age, we included 242 males from the Orientalizing-Archaic period (c. 800–500 BCE), and 161 males from the Hellenistic period (c. 400–27 BCE) from Abruzzo, central Italy (Sparacello, 2013). The subsistence of these individuals was based on pastoralism and agriculture throughout the Iron Age, however specialization of pastoral tasks led on average to low biomechanical mobility indices when compared to Ligurian Neolithic people (Sparacello et al., 2011). A marked decline in male upper limb asymmetry in torsional strength took place between the Orientalizing-Archaic and the Hellenistic period and was attributed to a shift in military organization from elite specialized militias to large conscript armies (Sparacello et al., 2015). Comparative sample sizes are dependent on the variable under examination (Tables 1 and 2).

2.2. Pathological and biomechanical methods

Pathological differential diagnosis was obtained through visual macroscopic observations, X-rays and CT scans. To evaluate possible systemic developmental disturbances due to disease, we compared the stature of individual OdN 410, obtained on the maximum femoral length, to the statures of male individuals from the same necropolis and other Italian samples. For the Neolithic and OdN sample, stature was estimated using the RMA formula in Formicola and Franceschi (1996); for the Iron Age sample, Pearson's formulae were used following previous research showing greater accuracy of these equations for this sample (Sparacello et al., 2017).

To reconstruct activity-induced functional adaptations, we analysed the cross-sectional geometric (CSG) properties of long-bone diaphysis. Bone tissue responds dynamically to bending stresses and strains to adapt to its mechanical environment (Ruff et al., 2006). The size and shape of long bone cross sections are analysed through the same principles used by engineers in designing structures, in this case hollow beams. It has been shown that CSG properties reflect the prevalent mechanical environment of an individual (Ruff et al., 2006), and the integration of CSG data with archaeological information has been widely used to make inferences about the subsistence strategies and mobility levels of past populations (Carlson and Marchi, 2014).

Cross sections of the OdN sample were obtained via medical CT scanning (University of Pisa Hospital); for several Neolithic individuals, the latex cast method was used, involving periosteal moulds and biplanar X-rays (O'Neill and Ruff, 2004). The solid method, based on periosteal moulds or surface 3D scans and regression equations (Sparacello and Pearson, 2010), was used for some Neolithic individuals and the entire Iron Age sample; cortical and medullary area size is therefore not available for these individuals/sample. The comparability of CSG data obtained through the different methods has been widely demonstrated (Stock and Shaw, 2007; Sparacello and Pearson, 2010; Macintosh et al., 2013).

In both humeri and the femur, we analysed the total area (TA) of the section, the area of the cortical bone (CA) and medullary cavity (MA; related to resistance to axial compression), and the polar moment of area (J, related to bending and torsional strength), which was used to calculate the section modulus ($Z_p = J^{0.73}$). Sections were taken at 35 % of humeral articular length and at 50 % of femoral mechanical length (following Ruff, 2002). To evaluate the residual strength, which can be attributed to physical activity, bone mechanical competence must be

Fig. 2. (A) Individual OdN 410 in supine position with extended limbs and a bronze sword placed on the right shoulder; (B) Magnification of both pathological glenohumeral joints at the time of excavation (dotted circles).

Table 1
Cross-sectional geometric properties, non-standardized by body size, in individual OdN 410 and the comparative sample.

Non-standardized CSG*	OdN 410**	Neolithic Liguria			Bronze Age OdN			Orientalizing-Archaic Abruzzo 800–600 BC			Hellenistic Abruzzo 400–27 BC		
		N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
TA HUM R	**392.56>>>**	19	291.79	32.34	11	296.40	21.72	222	341.91	45.26	149	352.87	50.28
CA HUM R	**272.59**	7	237.02	40.16	11	239.39	17.51						
MA HUM R	**119.97>>>**	7	69.68	14.41	11	57.01	8.63						
%CA HUM R	**69.44<<<**	7	77.06	4.97	11	80.79	2.27						
J HUM R	**22597.36>>>**	19	13145.59	3048.88	11	13756.08	2011.76	222	18082.86	4708.52	149	19387.90	5007.30
TA HUM L	**355.27>>>**	21	275.23	29.90	11	278.25	23.57	222	308.13	39.74	150	328.11	41.53
CA HUM L	**247.41**	7	217.67	31.20	11	226.12	18.60						
MA HUM L	**107.86>>>**	7	65.76	15.57	11	52.13	12.02						
%CA HUM L	**69.64<<<**	7	76.61	6.01	11	81.34	3.34						
J HUM L	**18747.48>>>**	21	11719.64	2654.81	11	12176.40	2037.87	222	14777.48	3857.95	150	16735.70	4285.21
TA FEM	**577.57**	18	535.84	60.26	11	585.98	53.63	168	615.53	71.37	122	624.64	80.70
CA FEM	**426.17**	6	422.93	65.01	11	446.43	34.28						
MA FEM	**151.40**	6	129.38	17.89	11	139.55	24.51						
%CA FEM	**73.79**	6	76.28	4.69	11	76.30	2.39						
J FEM	**50034.13**	18	46448.19	11343.40	11	53485.36	9210.43	168	58601.20	13458.32	122	60565.77	15970.82
BODY MASS	**73.95**	23	64.91	6.10	11	67.35	7.57	195	71.01	6.33	141	73.56	6.07
STATURE	**166.07**	13	158.19	5.02	11	168.59	7.79	124	165.76	8.29	101	165.61	4.04
HUM M2 R	**274.30<<<**	19	296.21	9.00	11	324.10	13.85	145	321.55	16.21	113	322.65	16.99
HUM M2 L	**273.40<<<**	22	294.30	11.23	11	322.32	14.84	143	314.71	15.36	115	314.40	16.14
FEM M18	**48.70**	23	45.88	2.48	11	46.49	2.72	195	48.10	2.70	141	49.20	2.57
FEM M1	**447.00**	13	416.12	19.68	11	456.91	30.54	124	449.20	44.07	101	448.41	21.50

* TA: total area of the cross section; MA: medullary area of the cross section; CA: cortical area of the cross-section; %CA: percent cortical area; J: torsional rigidity; HUM: humerus; FEM: femur; M1 and M2 indicate Martin's lengths; M18 is the femoral head's superior-inferior diameter.
** < and > indicate standard deviation above or below mean.

"standardized", i.e. scaled by body size (Ruff, 1995, 2000). Thus, Z_p was scaled by dividing it by bone mechanical length × body mass, while TA, CA, and MA by body mass alone (Ruff, 2000). Body mass was calculated from the femoral head supero-inferior diameter following Trinkaus and Ruff (2012).

Non-standardized CSG is usually not discussed in studies aiming to reconstruct activity-induced postcranial functional adaptations, because diaphyseal areal properties are proportional to body size. Given that we have analysed atypical variation in one individual we needed to gain perspective on the level of variation of the absolute size of the diaphyseal sections within and between samples. In addition, possible anomalies due to the pathological development of bones might be obscured when standardizing CSG properties using similarly pathological bone lengths or articular dimensions. We therefore provide results also for non-standardized CSG properties.

Indices derived from CSG properties might provide information

Table 2
Cross-sectional geometric properties, standardized by body size, in individual OdN 410 and the comparative sample.

Standardized CSG*	OdN 410**	Neolithic Liguria			Bronze Age OdN			Orientalizing-Archaic Abruzzo 800–600 BC			Hellenistic Abruzzo 400–27 BC		
		N	Mean	SD	N	Mean	SD	N	Mean	Std.Dev	N	Mean	SD
TA HUM R	**530.83**	19	464.80	51.15	11	444.42	51.25	181	486.67	60.35	131	481.21	59.14
CA HUM R	**368.61**	7	369.64	58.59	11	358.90	41.19						
MA HUM R	**162.23>>>**	7	108.55	20.84	11	85.52	15.12						
%CA HUM R	**69.44<<<**	7	77.06	4.97	11	80.79	2.27						
Z_p HUM R	**74.35>>>**	19	54.44	9.24	11	48.52	6.46	135	57.26	10.01	103	56.43	9.03
TA HUM L	**480.41**	21	426.634	48.73	11	416.24	42.40	181	436.60	51.77	133	445.39	53.52
CA HUM L	**334.56**	7	345.06	37.26	11	338.67	38.23						
MA HUM L	**145.85>>>**	7	105.55	30.44	11	77.57	15.61						
%CA HUM L	**69.64<<<**	7	76.60	6.014	11	81.34	3.34						
Z_p HUM L	**65.09>>>**	21	49.00	8.44	11	44.47	5.47	133	49.55	8.32	105	51.86	8.97
HUM BA	**20.54**	18	17.38	9.82	11	13.49	6.84	220	24.37	15.06	146	18.61	12.72
TA FEM	**781.01**	18	848.42	77.02	11	875.55	86.66	160	863.08	94.47	116	850.91	91.14
CA FEM	**576.28**	6	653.76	100.23	11	667.76	66.54						
MA FEM	**204.73**	6	200.18	29.59	11	207.79	30.64						
%CA FEM	**73.79**	6	76.28	4.69	11	76.30	2.39						
Z_p FEM	**87.58**	18	101.23	13.65	11	98.42	11.45	156	99.40	14.29	112	100.22	13.98
I_x/I_y FEM	**1.20**	18	1.32	0.21	11	1.05	0.21	168	1.07	0.18	122	1.06	0.20

* TA: total area of the cross section; MA: medullary area of the cross section; CA: cortical area of the cross-section; %CA: percent cortical area; J: torsional rigidity; HUM: humerus; FEM: femur; M1 and M2 indicate Martin's lengths; M18 is the femoral head's superior-inferior diameter; Z_p: section modulus; HUMBA: humeral bilateral asymmetry.
** < and > indicate standard deviation above or below mean.

about the types of activity performed by a group or an individual. In this study, we have analysed humeral bilateral asymmetry, calculated using the formula $[(J_{max} - J_{min}) / J_{min}] \times 100$ (Rhodes and Knüsel, 2005). Clinical evidence has demonstrated that high humeral asymmetry in J is associated with unimanual sports (Jones et al., 1977; Trinkaus et al., 1994; Shaw and Stock, 2009), while in bioarchaeological settings it has been attributed to hunting via throwing, woodworking, or weapon use (Churchill et al., 1996; Rhodes and Knüsel, 2005; Marchi et al., 2006; Sparacello et al., 2011, 2015). In the femur, we evaluate the shape index I_x/I_y (ratio of anteroposterior and mediolateral bending moment), a measure associated with mobility levels (Carlson and Marchi, 2014). To evaluate whether body proportions and CSG properties of individual OdN 410 were significantly altered by pathology, we considered three standard deviations (SDs) or more from the mean as a statistically significant difference of the Bronze Age population.

3. Results

Both humeri of the individual OdN 410 are much shorter than the average length of the OdN male sample (i.e., 4–5 cm shorter, +3 SDs below the mean, Table 1, Fig. 3). The humeri (Fig. 4) show morphological and destructive modifications at the proximal epiphyses consisting of a flattening of the joint surface with diffused large pitting and eburnation suggesting a severe condition of osteoarthrosis (Rogers and Waldron, 1995). The humeral head is not recognizable, the anatomical neck is absent, and both shafts are markedly curved at the level of the deltoid tuberosity. Both scapulae (Fig. 5) show large pitting and remarkable flattening of the glenoid fossa. The glenoid cavity and supra and infra-glenoid tuberosity, though displaying marked erosion, are still recognizable in the left scapula. With frontal X-ray inspection (Fig. 6), flattening of glenohumeral articulations and subchondral bone thickening are observable.

Table 1 shows variation in non-standardized CSG variables for

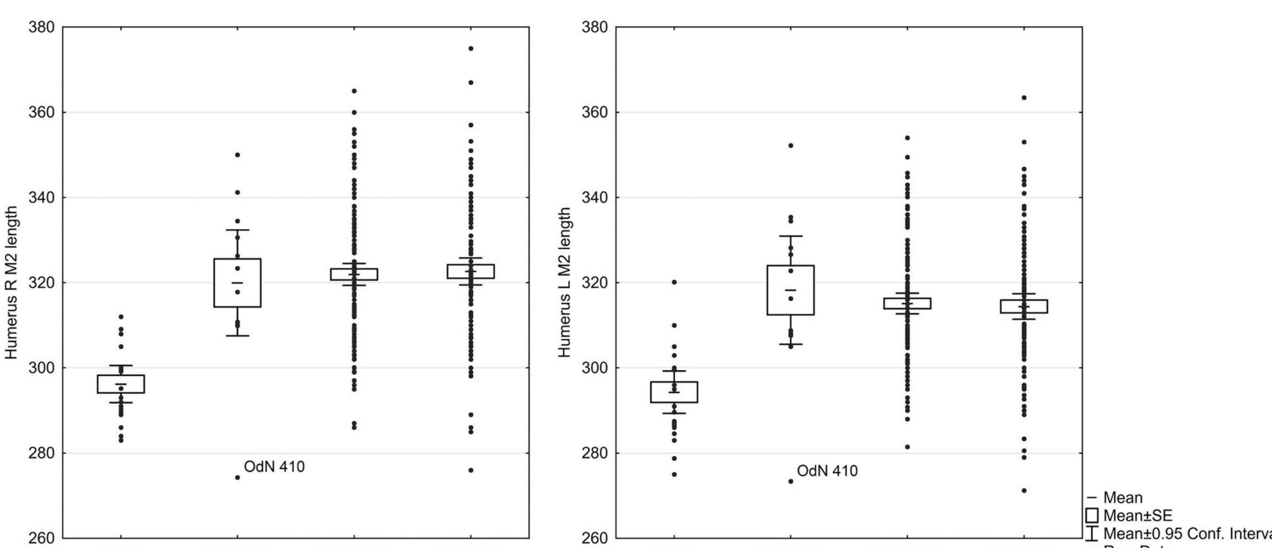

Fig. 3. Humeral physiological length (M2) of individual OdN 410 and comparative samples. NEOL: Neolithic from Liguria; BRONZE: Olmo di Nogara sample; IRON O-A: Orientalizing-Archaic Iron Age sample from Abruzzo; IRON HEL: Hellenistic Iron Age sample from Abruzzo.

Fig. 4. (A) Anterior view of both glenohumeral articulations of individual OdN 410. Note, the marked bilateral humeral varus resulting in reduction of humeral lengths, absence of surgical and anatomical neck and loss of the humeral head (scale in cm); (B) The surviving surfaces of the humeral head completely flattened, cribrotic, and eburneated suggesting serious degeneration of glenohumeral articulation.

Fig. 5. Detail of anterior glenoid cavities of the right (A) and the left (B) scapulae exhibiting flattening and macroporosity of subchondral plate.

individual OdN 410 and comparative samples, as well as the estimates of stature, body mass, and osteometric measurements analysed in this study. The Bronze Age individuals from OdN are closer in CSG dimensions to the Neolithic individuals from Liguria, they are as tall or taller than later Iron Age groups and appear of less stocky body proportions than the comparative samples. Individual OdN 410 fits well in body proportions with the rest of the Bronze Age sample having both femoral length and articular dimensions within one SD from the OdN mean, resulting in average stature and body mass estimates (Table 1).

The TA and MA of both humeri of individual OdN 410 are larger compared to his peers (+3 SDs), resulting in a significantly lower percent cortical area (-3 SDs). The increase in TA results in a significantly higher J in both humeri (+3 SDs when compared to the OdN sample), similar to the later Iron Age samples. Conversely, the non-standardized femoral TA and percent cortical area appear within the expected variability of the Bronze Age sample (Table 1).

When size-standardized (Table 2), the humeral TA of individual OdN 410 does not significantly deviate from the mean of the Bronze Age sample, being between one and two SDs from the mean. However, the increase of the humeral medullary cavity is still significant after standardization by body mass (+3 SDs). In addition, the marked size-standardized humeral robusticity (+3 SDs), resulting from the enlarged cross sections and shortened humeri, makes our individual amongst the most robust compared to the reference samples.

Average humeral bilateral asymmetry in the OdN sample is the lowest amongst the comparative samples (Fig. 7). However, individual OdN 410 is one of the most lateralized in the sample (humeral bilateral asymmetry = 20.54 %); further, it shows a value of femoral I_x/I_y of 1.2, which is within the expected variability of the OdN sample (Table 2).

4. Discussion

Individual OdN 410 has both humeri characterized by marked shortening in length associated with a postero-medial rotation of the shafts, referred to as a type of bone dysplasia known as humerus varus (Ogden et al., 1976; Ellefsen et al., 1994). This could be the result of hereditary, metabolic, infective, or traumatic disease (Hamlet, 2007). The adult age and the absence of others pathological changes in the skeleton lead us to reject a diagnosis of thalassemia (Hershkovitz et al., 1991; Lagia et al., 2007) or mucopolysaccharidoses (Ortner, 2003:490). In metabolic diseases such as rickets, humerus varus is sometime observable, but lower limbs are usually affected by bending secondary to

Fig. 6. Radiograph showing marked thickening of the cortical bone, curvature of the deltoid area and osteosclerosis involving the shoulder joints of individual OdN 410.

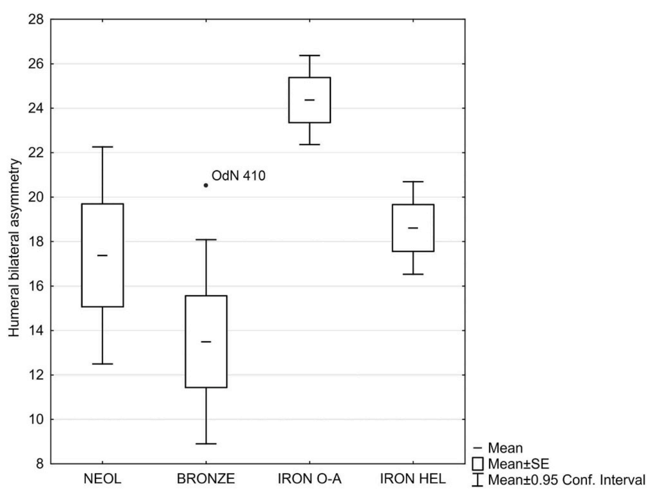

Fig. 7. Humeral bilateral asymmetry in torsional rigidity (J) of individual OdN 410 and comparative samples. NEOL: Neolithic from Liguria; BRONZE: Olmo di Nogara sample; IRON O-A: Orientalizing-Archaic Iron Age sample from Abruzzo; IRON HEL: Hellenistic Iron Age sample from Abruzzo.

weight bearing (Kacki et al. 2013), and this is not the case for our individual. Indeed, the rest of the skeleton showed no other pathological evidence and consequently this confines the diagnosis to a trauma that occurred at time of birth, probably an epiphyseal fracture (Anderson, 1997, Molto, 2000; Kacki et al., 2013; Sperduti et al., 2022).

Humeral shortening in length and abnormal angulation of the epiphysis is observable when a physeal injury during development disrupts the necessary blood supply to the growth plate (Resnick, 1995; Verlinden and Lewis, 2015). In the palaeopathological literature, twenty cases of both unilateral and bilateral humerus varus were described, ten of which were interpreted as the probable result of epiphyseal injuries that occurred to the child at the time of delivery (Sperduti et al. 2022). Amongst these ten, the palaeopathological case most directly comparable with individual OdN 410 in terms of severity of skeletal changes is the one described by Molto (2000), an adult male from the Roman necropolis of Dakleh oasis (Egypt), dated to 300–390 AD.

Bilateral humeral varus is less common than unilateral, occurring in 0.2–5.1 per 1.000 births (even though some studies reported a prevalence of 22 % in smaller samples) and is prevalently observed as a consequence of injuries related to shoulder dystocia and breech delivery (Nath et al., 2007; Piatt, 2004; Okulczyc et al., 2013; Blaauw et al., 2004), when the pubic bone or sacral promontory impedes progression of the foetus in the birth canal. In this critical situation for the life of both baby and mother, modern obstetric protocols prescribe a set of manoeuvres or as last resort, a caesarean section (Mir and Ahmad, 2010). In this context, epiphyseal trauma is not uncommon, and we might expect that forced manoeuvres to facilitate birth of the baby were probably more frequent during the Bronze Age. Another risk to the foetus is the tear or compression of the nerve roots of the brachial plexus (typically C5-C6) due to violent traction or incorrect manipulation, which can result in upper limb palsy (loss of motor function). Typically, the palsy is temporary and most of patients recover arm function within one year (Gherman et al., 1999). This is what probably occurred in our case, as no evidence of gracility due to flaccid paralysis was macroscopically observed on the upper limbs. To further investigate this issue, we examined the humeral structural properties.

The analysis of long bone functional adaptations is generally aimed at the reconstruction of activity patterns in the past and is therefore based on a sample deemed representative of a population (Meyer et al., 2011; Jurmain et al., 2012). Indeed, individuals vary significantly in biomechanical properties, even when subsistence activities are expected to be homogeneous; therefore, CSG properties of individuals are not used to reconstruct activity patterns. Significant deviations from the norm of the reference population have been used to discuss disturbances in average bone development due to disease and disuse, either due to debilitating conditions or trauma, aiding the reconstruction of the osteobiography of specific individuals (e.g. Sparacello et al., 2016, 2023; Gilmour et al., 2019, 2022, 2023).

The analysis of postcranial body proportions and functional adaptations suggests that humeral changes in individual OdN 410 are not the result of a systemic developmental disturbance (e.g. Sparacello et al., 2016). Body proportions, as reconstructed from stature and body mass, appear within the range of variability in the OdN sample. Likewise, CSG properties of individual OdN 410's femur are similar those to his peers, both in absolute values and after scaling for body size. In addition, his femoral shape index, which is influenced by terrestrial mobility levels (Holt, 2003; Carlson and Marchi, 2014), is among the highest in the OdN sample. We prefer not to make inferences regarding individual mobility levels, however an indication of muscle atrophy would be expected associated if there was long-term inactivity. In fact, the orientation of femoral maximum bending rigidity shifts from medio-lateral to antero-posterior around 8–10 years of age, due to changes in body proportions and gait patterns (Cowgill et al., 2010; Gosman et al., 2013). Our results therefore suggest that the individual analysed here displayed average levels of mobility.

Postcranial functional adaptations mainly affected the upper limbs. In addition to the bilateral shortening in length, the analysis of the mid-distal diaphyseal CSG properties indicates significantly enlarged total and medullary areas, leading to a markedly low percent cortical area. The functional interpretation of individual OdN 410's upper limb CSG is challenging, given that diaphyseal CSG properties are the result of complex interactions between body size and activity levels (Lazenby, 1990; Pearson and Lieberman, 2004), genetic factors (Rauch, 2005) and, in this case, pathology during ontogeny. Clinical studies have shown that, in the absence of environmental disturbances, the TA of a bone section, which is the main determinant for mechanical rigidity (Stock and Shaw, 2007), is positively correlated with activity levels during the pre- and peri-pubertal periods (Bailey et al., 1999; Pearson and Lieberman, 2004; Baxter-Jones et al., 1985). In contrast, lack of activity during growth inhibits periosteal apposition, leading to small TAs (Ruff et al., 1994; Sparacello et al., 2016), especially in individuals with early onset and long-term debilitating pathologies (Kovacs, 2008). The high values of humeral TA in individual OdN 410 may indicate that his upper limbs were not immobilized or severely impaired from a young age. On the other hand, it is difficult to imagine that his extremely large TAs are solely the result of vigorous activity during the pre- and peri-pubertal period, and that his pathology did not play a role. In fact, another individual with unilateral humerus varus from the Medieval (and therefore presumably untreated) Graveyard of La Madeleine (France) (Kacki et al., 2013) has enlarged TA of the cross sections in the pathological limb compared to the contralateral side (Kacki, personal communication).

A factor that might influence cross-sectional development of shortened limbs is mechanical disadvantage. While bone shortening may theoretically lead to a reduction in bending moments, which could be sustained with a smaller TA, the "muscle bone unit" should be considered (Frost and Schönau, 2000) to explain the enlarged TA of our individual. It is possible that because of his mechanically disadvantaged leverage in the upper limb, he required a larger muscle mass, especially in the deltoid and brachialis, to perform the same tasks of his peers. Experimental research showed that varus deformity decreased the efficiency of the supraspinatus and increased deltoid elevation forces (Voigt et al., 2011). The enlarged humeral TA could be at least partially due to an anomalous and vigorous pulling of muscles on the periosteum. As seen above, the size and roughness of muscular insertions in our subject appear to agree with this scenario. Although it is difficult to determine the degree of impairment suffered by this individual, especially later in life due to degenerative joint disease to the glenohumeral joint, results suggest that individual OdN 410's upper limbs were used in an active lifestyle.

Humeral asymmetry in torsional strength suggests the preferential use of one arm in stressful tasks, such as hunting via throwing (Churchill et al., 1996; Sparacello et al., 2017) or weapon use (Sparacello et al., 2011, 2015). As an index, humeral asymmetry has the advantage of factoring out the effect of body size on CSG properties, which is only imperfectly considered when standardizing other CSG properties (Ruff, 2000). Given that the level of degeneration to the proximal humeral epiphysis in individual OdN 410 is similar bilaterally, it is possible that its effect on CSG properties can be factored out, as well. In this case, humeral lateralization in mechanical competence could provide insights into this individual's daily activities. In the OdN sample, average humeral asymmetry is around 13 %, not very different from modern samples (8–10 %) composed of generally non-active individuals (Shaw and Stock, 2009). However, the OdN sample appears split between individuals with low values (6–7 %) and individuals with high values of lateralization (15–23 %). Interestingly, the two groups appear to have some correspondence with the presence or absence of a sword in the burial, the sword being more common in the more lateralized group. Although a larger sample is needed to confirm this result, it is worth noting that our individual belongs to the "higher asymmetry" group (20.5 %) and was buried with a sword. It is therefore possible that his CSG properties were partially shaped by the use of weapons, at least at some point during his life.

Overall, humeral mid-distal CSG properties of individual OdN 410 are probably the result of a complex interaction of factors, among which the disruption of the epiphyseal plate and altered morphology. No clear indication of long-term lack of activity, or even immobilization during growth is present. It is likely that our individual actively used the upper limb, possibly preferentially the right one. This is compatible with the clinical literature suggesting that functional impairments are rare in individuals with humerus varus (Ogden et al., 1976; Ellefsen et al., 1994; Peterson, 2007; 2012), and that these individuals can develop a marked muscular robustness of the deltoid and biceps (Davies, 1956).

Individual OdN 410 shows severe osteoarthrosis of the glenohumeral joint, which most likely led to a severely limited range of motion, especially abduction of the arm later in life. The risk of secondary osteoarthrosis later in life in individuals with developmental humerus varus has not been investigated in the clinical literature. Nevertheless, in studies analysing malunion of the humeral head after fractures in adult subjects, an increased risk of secondary osteoarthrosis is expected, given the dysfunction caused by direct abutment or rotator cuff insufficiency (Duparc, 2013). Once the glenohumeral joint begins to erode, articular forces increase dramatically, facilitating continued bone degeneration (Farron et al., 2009). It is therefore possible that the extreme degeneration observed in individual OdN 410 are the consequence of vigorous use of the upper limbs in a context of glenohumeral instability, predisposing the individual for secondary osteoarthrosis.

Overall, it appears that the dysplasia of individual OdN 410, although accompanied by mechanical disadvantage and increasingly severe impairments later in life, may not have been perceived as a disability by himself or his peers. In fact, this individual was associated with military paraphernalia in his mortuary context, similar to 40 other males in the same cemetery. The humeral structural properties suggest that the humerus varus did not prevent or exempt this individual from performing vigorous activities, possibly the use of the recovered sword itself. Moreover, the presence of weapons does not appear to have been merely symbolic since 14.5 % of the male sample at OdN shows signs of sharp force wounds or embedded arrow points (Canci and Salzani, 2020) –indicators of interpersonal violence. The possibility that individual OdN 410, despite his limitations, devoted himself to the use of weapons, could provide insights into the societal presence of interpersonal violence or warfare amongst the people from Olmo di Nogara.

5. Conclusions

The individual buried in Tomb 410 of the Olmo di Nogara Middle Bronze Age cemetery presents a skeletal dysplasia consisting of bilateral humerus varus, which was probably caused by trauma during birth (breech or shoulder presentation). Forced and vigorous manipulation likely performed by a birth attendant to disengage the foetus resulted in fracture of the physes of both humeri impeding proximal growth of both humerus shafts, and probably temporary palsy. Despite the reduction in upper limb length, the mechanical structural adaptations indicate that the individual did not have a reduced range of abduction and flexion. The biomechanical findings, alongside contextual interpretations, suggest he had an active lifestyle and possibly used weapons. Indeed, the funerary accoutrements associated with this individual does not set him apart from other male peers buried with swords. However, the progressive wear of the glenohumeral joint caused by humerus varus led to severe osteoarthrosis, which greatly limited the abduction and flexion movements of the arm in the final phases of his life.

CRediT authorship contribution statement

Damiano Marchi: Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Alessandro Canci:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Vitale Stefano Sparacello:** Writing – original draft, Methodology, Investigation, Formal analysis. **Davide Caramella:** Visualization, Investigation.

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