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Range of motion and energy cost of locomotion of the late medieval armoured fighter: a proof of concept of confronting the medieval technical literature with modern movement analysis

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Abstract [subtitle]

Study of technical, normative and narrative medieval literature and of archaeological pieces, allows the motor skills of armoured members of the aristocracy to be outlined, but not quantified. We present novel data on the impact of wearing armour on both the freedom of movement and the energy cost of locomotion and confront the results to systematic analysis of medieval written sources. An accurate harness replica realised in an informed archaeological experimental way, close to medieval material and manufacturing conditions, was used for the experiments. Measurements the energy cost of locomotion in and out of armour were taken during walking and running on a treadmill. Gait analysis and range of motion of joints were performed with 3D kinematics. The results indicated an increase in the energy cost of locomotion in slight excess to the added weight and for most movements studied reductions in the range of motion over the joint, potentially to the advantage of the wearer during combat. This proof of concept appears promising for further study in this field of scholarly endeavour.

Keywords: biomechanics, locomotion, range of motion, Fight Books, Medieval armour, energetics.

Introduction [subtitle]

At the end of the fifteenth century, Pietro Monte, famous condotierre and master of arms (Fontaine 1991), wrote in his Fight Book [1], that armour should combine three conflicting qualities: "lightness, protection and freedom of movement" [2]. Such was the perfection reached that NASA (National Aeronautics and Space Administration) engineers used Henri VIII's foot combat harness design of 1520 to develop the first space suit in the 1960s (Richardson 2013). Nevertheless, fighting in armour weighing 18 to 30kg imposed a heavy physiological burden and medieval knights had to train. Jean le Meingre, known as Boucicault, a famous French knight at the turn of the fourteenth century, was reported to train in armour by pulling himself up by his arms hanging free under a slanted ladder; by running to improve his breathing, or by jumping on horseback without the help of stirrups, and even by performing somersaults, fully armed except for the head (Lalande 1985: 26).

The fifteenth century was the golden age of plate armour - referred to as "harness" -, composed of articulated plates of hardened steel, partially fastened onto a complex undergarment made of textile and possibly leather, and reinforced with mail defences (the so-called arming doublet, see Capwell 2002). Depending on its purpose (warfare, tournament, normative combat on foot or on horseback) and the status and wealth of the owner, the type, quality and mass of armour varied greatly (Williams 2003). Because of the high quality protection offered and the effects on the wearer's biomechanical characteristics, authors of Fight Books described specific techniques that were separate from the other technical repertoire of unarmed combat and fighting on horseback (Jaquet 2013b). This technical literature, for the major part, addresses an audience familiar with the art of combat (Müller 1992), using image and/or text. Its function is still a subject of debate, but it is generally accepted that it served all or some of the following: mnemonic support, didactic manual and discursive medium. However, a modern reader who wants to perform the described techniques will lack the knowledge of arms and armour, the technical lexis and more specifically the embodied knowledge of medieval combatants [3].

With a perspective of the impact of wearing armour during medieval warfare, Askew et al. (2012) analysed the energy cost of locomotion (Cmet) and kinematics of walking and running on a treadmill on four subjects wearing harnesses. They found a Cmet value 2.1 to 2.3 times higher for walking, and 1.9 times higher for running when compared with unloaded locomotion, but they did not study the limitations imposed by the armour on freedom of movement of the wearer. Furthermore, those authors chose armours that were not representative of the subject of their inquiry and did not relate their analysis to the technical medieval literature. Instead, they referred to a disputable literary account of a battle predating, for at least two generations, the armour typology of the worn replicas.

Here we present the results of an interdisciplinary approach bringing together historians, physiologists and biomechanics specialists, to confront an in depth historical analysis of medieval sources such as Fight Books, with a modern movement laboratory-based analysis of the impact of wearing a faithful replica on a contemporary subject. We contend that such an approach produces valuable data serving inquiries that cannot be solved with an analysis of historical sources alone. The limits of such approaches have been criticised previously, especially with regard to the concept of "historicising the body", even though recent publications have argued otherwise [4]. Our approach should be seen as a proof of concept. We had access to a single subject who was knowledgeable of the studied medieval Fight Books and who had trained for several years the various moves and gestures from those sources. We believe that such an approach allows an evidence-based approach towards a modern era enactment of technical gestures related to single combat in armour, and also that modern physiological and biomechanical analysis of movement in armour would allow grounding the experiment.

Material and Methods [subtitle]

a. Historical sources [subtitle – 2nd level]

The most reliable sources about gestures performed in personal combat of the fifteenth century are so-called "Fight Books". These are non-fictional, technical literature authored by combat specialists for an audience of educated and trained fighters (Müller 1992a, 1992b). They are not a relation of combat in chronicles or chivalric romances based on eyewitnesses' testimony or earlier written sources. This literature is to be connected with normative combat, i.e. ruled by norms or standards, e.g. the plurality of chivalric games in a playful context, but also single combat in more serious situations such as judicial duel, duel for honour or self-defence (Vale 1981:76; Jaquet 2013b: 349-406). Importantly, there is no direct evidence of a connection with warfare (Anglo 2000:271; Tlusty 2011:211) or with the training of men-at-arms (Jaquet 2013b:407-421; Malszecki 2010). To support our studies and experiments, we used a comprehensive corpus of 13 specialized treatises or sections of treatises regarding the technical repertoire of fighting on foot in harness, produced in a geographical area from the South Rhinelands down to Northern Italy, from the period 1410-1510, represented in 36 manuscripts (Appendix 1). This corpus of Fight Books is heterogeneous; each witness must therefore be studied independently and great caution towards generalisation must be upheld. Any alleged representative value must be put in context and questioned.

b. Suit of armour, subject [subtitle – 2nd level]

The laboratory-based experiments were performed on a male subject (age 30yrs, height 186cm, weight 84kg [5]) in and out of an accurate replica of a well-preserved mid-fifteenth century harness with a design that matches the representations of 1470s Paulus Kal's Fight Book (Figure 1). It was made to measure and was realised in an informed experimental archaeological way, to replicate as closely as possible its mechanical properties, but also its visual aspect (Appendix 2). The replica and the arming doublet worn represented 46% of the body mass of the subject, which is comparable to the marching loads for infantry units post Word War II (Knapik et al. 2004), or to the equipment of a contemporary fireman. This load would correspond to that of a princely harness covering the whole body for normative combats – as represented in the Fight Books. It is not representative of other type of armour, e.g. field armour or armour worn for campaign, usually weighing up to 5-10 kg less [6]. The subject was trained by performing physical exercises regularly wearing the replica, allowing him to walk, run and experiment the technical moves and gestures according to the repertoire from the Fight Books (Appendix 1).

[Here Figure 1. Comparison between the original suit of armour, the representation of its typology within the Fight Books' corpus and the replica worn for the experiments.
Left panel: Suit of armour of Frederick Ist, steel and leather, several Milanese workshops, ca. 1450, © Wien, Kunsthistorisches Museum, Hofjagd- und Rüstkammer, Inv.-Nr. A 2. Center panel: Representation of a pair of armoured fighters in Paulus Kal's Fight Book (1459-1479), Paper, © München, Bayerische Staatsbibliothek, Cgm 1507. Right panel: Replica, steel and leather, photo by E. Jaquet.]

c. Energy cost of locomotion [subtitle – 2nd level]

The subject walked and ran on a motorised treadmill, once wearing shorts and running shoes and once in armour (Video 1). Pulmonary gas exchange was measured according to routine technique on a breath-by-breath basis with indirect calorimetry (Quark, Cosmed, Italy). The device was calibrated before the experiment with gas mixtures of known composition and a 3L syringe. After resting measurements standing on the treadmill, the subject started to walk at 2km/h for 4min after which the speed was increased by 4min increments of 1 km/h until 8km/h, after which incremental steps of 2km/h followed, until voluntary exhaustion. The transition from walking to running was spontaneous. Gas exchange was analysed for the last 30-60 sec of each step. Oxygen uptake was transformed into kcal/min using a 5kcal/l equivalent with no correction for respiratory quotient changes. We interpreted the maximum oxygen consumption attained, while running in shorts and running shoes, as the subject's maximum aerobic capacity.

d. Range of motion during gait movements and functional movements [subtitle – 2nd level]

A three-dimensional (3D) movement analysis was performed during two separate sessions in order to measure, to quantify, and then to compare the range of motion (ROM) of each body joint of the subject in and out of armour. The subject was first studied while walking (Video 2), and then during more complex and maximal functional movements for each body joint (Videos 3 and 4).

The first session, without the full armour, was done with a 3D, 12-camera motion analysis system (Vicon MX3+, Oxford Metrics, UK), used to capture full-body motion (Video 5). Passive reflective markers were placed directly onto the skin at defined anatomical and technical points usually used to define body segments: on the head, arms, pelvis and lower limbs according to the Davis et al. (1991) protocol, and on the trunk as described by Gutierrez-Farewik et al. (2006). The marker trajectories were filtered using the predicted mean-squared error (MSE) adaptive filter within the Nexus software, version 1.8.5 (Oxford Metrics, UK). Joint kinematics were generated using the dynamic model (Vicon Plug-in-Gait, Oxford, UK).

During the session in full armour, the passive reflective markers were placed directly on the harness at specific landmarks closest to the defined anatomical and technical points used to define body segments in the first session. Then, as for the first session, marker trajectories were filtered using the predicted mean-squared error (MSE) adaptive filter and joint kinematics were generated using the dynamic model. To limit reflection artefacts, the number and resolution of cameras of the 3D motion analysis system were increased (24 x MXT40S, Vicon, Oxford Metrics, UK). Moreover, an additional filter was used to discard the reconstructed markers of incorrect radius.

For both sessions, the subject was asked to execute exactly the same movements. The subject was first asked to walk (barefoot without armour and with specific shoes with armour) at a self-selected speed along a 12-meter walkway. Data was collected for at least 5 gait cycles and was averaged. The subject was then asked to execute maximal flexion/extension movements, adduction/abduction movements and internal/external rotation movements for each body joint: ankles, knees, hips, pelvis, shoulders, elbows and wrists (Kapandji 2005). Again, data for 5 trials for each movement was collected and averaged to generate single angular displacements of the wrist, elbow, shoulder, thorax, pelvis, hip, knee and ankle joints/segments.

In the two types of movement, kinematic curves were calculated for each body joint, using Nexus 1.8.5 software (ViconPeak®, Oxford, UK), Matlab 2012a (MathWork, USA) and the open-source Biomechanical ToolKit package for MATLAB (Barre/Armand 2014). For each joint kinematic curve and each movement, the range of motion (ROM) value was calculated.

Results [subtitle]

a. Historical sources [subtitle 2nd level]

For the purpose of this study, we present an analysis of the technical vocabulary describing movements of attack, with an emphasis on upper limb motor-skills, from one non-illustrated treatise. The treatise "Shortened sword from the four guards" is considered an authoritative source, being represented in 14 witnesses, first compiled in 1450, and last copied in 1570 [7]. This text is composed of 36 paragraphs presenting sequences of movement, referred to as "piece" (*Stuck*). The text is organized by 11 rubrics, partitioning the treatise according to four guards' positions. The last part deals with techniques under a categorisation named as "setting the point" (*Ansetzen*). None of the 36 paragraphs or techniques bears a given name. The pieces may include single or multiple techniques, some of those being counter techniques to previous actions. At least 42 different techniques can be distinguished, mainly dealing with the handling of the long sword, but also include wrestling techniques (hand-to-hand locks and throws, see Video 6).

[here Table 1: Action verbs for offensive actions in "Shortened sword from the four guards" Manuscript of reference Rome, Accademia Nazionale dei Lincei e Corsiniana, Cod. 44 A 8, fol. 87r-90v. Edition Hagedorn (2008: 238-248). English translation Jaquet.]

Table 1 present the action verbs used by the author to describe offensive actions related to the upper body (vocabulary concerning footwork and displacements is not shown), with elements of description, technical comments and examples of the action in the context of a piece (i.e. one action composed of several movements).

In the first piece, the weapon's handling is described as: "take the sword with both hands and do so with strength" [8]. It matches the handling technique known as "half sword" or "shortened sword" described in more detail and illustrated in other sources (Appendix 1). Keeping one hand on the handle and placing the other on the blade allows both precision and strength for thrusting actions. All the actions described are performed with this specific grip, except for one where both hands are placed on the blade, in order to use the pommel as a hammer. There is no account of the use of the weapon with both hands on the grip, wielding the sword to strike with the edges. The reason is that the harness renders such handling in offensive actions ineffective. The consequence is that the offensive actions are performed mainly by pushing the sword in forward/backward and up/down motions. Indeed, most of the techniques described for attacking are thrusting actions, aimed at weaknesses in the opponents' harness [9]. Since these actions require great range of motion for the adduction/abduction of the shoulder and flexion/extension of the elbow, the design of the harnesses is such that both of these movements are only little constrained (see Table 4).

b. Energy cost of locomotion [subtitle 2nd level]

Figure 2 shows the oxygen consumption during walking and running with and without armour. One can observe the typical non-linear relationship for walking and the near-linear relationship for running. During walking the use of armour led to an on average 66% increase in the oxygen consumption for any given speed, with a slightly greater effect at higher walking speeds compared to lower walking speeds.

[here Figure 2. Oxygen consumption during walking and running with and without armour. Top panel, absolute oxygen consumption, which reached maximum aerobic capacity in both instances (with and without armour), as indicated by line A. Bottom panel, relative values normalized for body mass with and without armour. Line A represents relative aerobic capacity normalized with body mass and line B with mass of the armour added.]

c. Range of motion during gait analysis and static functional movements [subtitle 2nd level]

The results of the gait analysis are shown in Figure 3, and the data is shown in Table 2. Detailed results of range of functional movements for each joint can be seen in Tables 3 (lower limb) and 4 (upper limb).

[here Table 2: Range of motion of the joints during the gait cycle without and with armour. Range of motion (ROM - in degree (°)) during the gait cycle for the: ankle, knee, hip, pelvis and trunk joints in the sagittal plane (flexion/extension movement and tilt movement). The data corresponds as the mean values calculated for a minimum of gait cycle with standard deviation (in parenthesis).]

[here Table 3: Range of motion of the lower limb joints during maximal functional movements without and with armour
Range of motion (ROM) and standard deviation (STD) of: hip, knee and ankle joints during specific maximal functional movement without and with armour. Flexion – Extension: Flex/Ext; Abduction – Adduction: Abd/Add; Internal and external rotation: RI / RE.]

[here Table 4: Range of motion of the upper limb joints during maximal functional movements without and with armour.
Range of motion (ROM) and standard deviation (STD) for trunk, arm, elbow, and wrist during specific maximal functional movement without and with armour. Flexion – Extension: Flex/Ext; Abduction – Adduction: Abd/Add; Internal and external rotation: RI/RE.]

[here Figure 3. Joint kinematics, in the sagittal plane, of the lower limbs and trunk during the gait with and without armour.
The two columns present the kinematic curves (in degrees) obtained for the subject in the sagittal plane for the right limbs in blue (without armour) and cian (with armour) and for the left limb in red (without armour) and orange (with armour). The vertical lines indicate the end of the stance phase. Positive angles indicate a dorsiflexion of the ankle, a flexion of the hip and knee, and an anterior movement of the pelvis and trunk.]

Concerning the gait analysis in and out of armour, the ROM for the pelvis, trunk, hip and knee were similar, contrary to the ROM of the ankle (29.0° ± 1.8° without armour vs. 40.0 ± 1.7° with armour, Table 2). For all measurements (5 repeats for each movement were averaged), SD was low.

Concerning the maximal functional movement, some ROM were lower with armour compared to those without, such as flexion-extension of the hip, adduction-abduction of the hip and, flexion-extension of the knee (Table 3). The internal-external rotation movements of the leg were similar in and out of armour. For the upper-limbs, as for the lower limbs, movements were smaller with armour. Finally, the trunk movements in and out of armour were similar in terms of bending and rotation (Table 4).

Discussion [subtitle]

a. Historical sources [subtitle 2nd level]

Representation of types of harnesses in the Fight Books varied in details throughout the period, but can overall be classified as typologies meant to fight on foot (also known as foot combat or tourney armour) [10], for members of the upper and lower aristocracy. The Fight Books' technical repertoire reveals very detailed and complex systems of martial art, specialised for single combat on foot with harness and should not to be considered as representative for "soldiers" in a battlefield situation. The interpretations of the codified or described gestures are of course debatable and their experimentation is subject to several limits as mentioned above. However, the analysis of objective data can lead to relevant observations about mobility.

Overall the historical corpus studied indicates that close to half of all techniques, with all weapons concerned (spear, poleaxe, sword, dagger), are meant to throw the opponent to the ground (Jaquet 2013b:379-392). But this contention must not be over-interpreted, i.e. leading to the conclusion that an armoured fighter once lying on the ground cannot stand up again.

One of the most copied texts of the corpus contains a dedicated part on how to fight in armour while on the ground, but also how to stand up again [11]. However, it reveals that the high quality of the harnesses renders inefficient most of the conventional attacks and that the close-fighting distance would lead inevitably to wrestling exchanges (Video 6; Jaquet/Schmuziger 2011; Jaquet 2013b:389-393). Also noteworthy is that most of chivalric game exchanges were interrupted once a fighter was disarmed or thrown to the ground [12]. Some of the technique descriptions in the corpus conclude with the instruction to "conduct the opponent outside the barriers" (Jaquet 2013b:388), thus enforcing the connection with this rule-based chivalric context of application. Nevertheless, single combats could also have a more serious dimension (trial by battle, chivalric combat for honour) and lead to the use of the deadly techniques also described in the corpus.

A close reading combined with experience of the enactment of selected codified techniques (in experimentation context) reveals what can be framed as underlying martial principles. If these are not formulated explicitly (the Fight Book's author presumably assumes his readers are knowledgeable), some can be deduced by analysis. Relevant for this paper is the importance of the economy of movement, both for footwork and for using the weapon. This is not only connected with the need to limit unnecessary movement to save energy expenditure, but also to avoid exposition of weaknesses in the harness located in the joints (armpits, inner elbows and wrists are all specific targets to thrust actions) [13]. Therefore the extension of the arm for example is limited by the harness articulation (see Table 4), but is also useless and tactically dangerous in a combat situation, provided that none of the offensive bladed action requires an arming motion that goes above the head, implying a full extension of the arm (see Table 1).

b. Energy cost of locomotion [subtitle 2nd level]

The best design of armour according to Pietro Monte combined three conflicting qualities: lightness, protection and freedom of movement (see Note 1). The trade-off between those qualities, in our case study defined by a replica produced in an informed archaeological experimental way, imposed an added weight of 39.8 kg to the wearer, including the weight of the arming doublet with the mail gussets (7kg). This harness increased the energy cost of locomotion during both walking and running. The average increase amounted to 3.92 kcal/min (+66%). During running maximum aerobic capacity was reached at a lower speed (10 vs. 12 km/h) while carrying the armour. It can therefore be expected that wearers of such armour would have been disadvantaged in genuine conflict situations when confronted with opponents wearing lighter gear, but when confronting opponents equipped with similar gear, as in normative single combats, both combatants would have been limited to equal proportions.

The energy cost of walking without armour in humans is non-linear with a nadir corresponding to the spontaneous speed of walking. By contrast, the energy cost of running is near linear. We tested the hypothesis that the energy cost of walking and running would increase in proportion with the added weight of the armour. This appeared to be only partly the case, as can be seen in Figure 2. The relationship between absolute oxygen uptake (i.e. energy expenditure) and speed was shifted upward (upper panel) while the relationships overlap after normalisation of oxygen uptake for the sum of body mass and gear (lower panel). In our subject the 46% increase in mass of the armour led to an on average 66% increase in the energy cost of walking. Askew et al. also observed an increase in the cost of locomotion in armour greater than expected from the added mass only (110-130%). They suggested that because the armour is distributed over the entire body, it is different from carrying an equivalent mass in a backpack (Askew et al. 2012). We tentatively explain our differing findings to partly result from our experimental conditions with correct fixation of the cuisses and poleyns (laced on the arming doublet as opposed to suspended to a modern belt), which plays a central role in allowing a good mass distribution over the whole body, provided that the arming doublet is correctly tailored.

It would be interesting to pursue these types of analysis in more detailed fashion. Performances and weight of these defensive armour pieces depend on shape, thickness, hardness and quality of the iron used for production (carbon, phosphorus and slag content, see Williams 2003:927-944 and Dillman/Pérez/Verna 2011:xx-xx). Depending on its primary purpose (warfare, foot combat, mounted combat, chivalric games, etc.), and the status and wealth of the owner, the type, quality and mass of suits of armour varied greatly (Edge/Paddock 1988:173; Fallows 2010:125). Also, the same person would use different pieces for different purposes; there is even evidence for specific armours designed for chivalric games only, which would not be worn in other circumstances (Williams et al. 2012). For example, the head's defence used in our experiments was of the great bacinet-type, meant for foot combat and weighting 5.9kg, as opposed to a so-called sallet-type specifically meant for mounted combat with a mass down to 3kg or less – a better choice for warlike situations on horseback or on foot where the weight issue, the neck mobility and vision are of greater importance, leading to an overall lighter ensemble [14].

But in order to measure the full effect of wearing armour, the mass of the arming doublet should be added to the mass of the different pieces of the armour. Unfortunately, no complete authentic archaeological corresponding arming doublets have survived. Experimental replicas based on written descriptions and partial remnants can weigh from 3 all the way up to 10kg, mainly depending on the type of the mail defence sewn or worn upon (Williams 1980).

It is therefore highly disputable to argue a "typical" weight for an "armoured soldier" as proposed by Askew et al. (2012), especially when taking into account the narrative descriptions of battle situations, where information about weight of the equipment may serve other purposes than objective observation. Furthermore, the battles cited by Askew et al. largely predate the replicas they used for their experiments, undermining their conclusions and some of their statements, especially about the weight issue and the disputable assumption on the difficulties to stand up once being on the ground [15].

The mass of the armour we used was representative for the typology of the harness in the context of the medieval sources analysed (ca. 1410-1510), likely designed for chivalric games and not for warfare. Nonetheless, it matches the average mass of the armour used by Askew et al. (35 ± 5kg, representing 44 ± 3% of the individuals' body mass).

c. Range of motion during gait analysis and static functional movements [subtitle 2nd level]

We found that wearing armour had little impact on the most natural human movement, i.e. walking. Analysis of gait yielded similar values in and out of armour, as shown in Figure 3 (average differential of 2.48°), except for the ankle joint movement with a difference of 11° between the two conditions. While wearing armour, an increased ankle dorsiflexion was observed during the stance phase of the gait. We think that this change in walking pattern could be due to the modification of limb weight and inertia from the added mass with the armour leading to an adaptation to the novel limb dynamics. In agreement with findings by Noble and Prentice (2006), this increased ankle dorsiflexion observed could ensure an adequate amount of lower limb clearance during the transition to the new mechanical constraint acting on the lower limb kinematic with the armour.

The harness was not a constraint to achieve natural walking movements for the hip and knee joints. For the ROM measure of maximal functional movements, most were constrained by the harness (average differential of 19.9°). For example, the largest restriction of movement found concerned the flexion-extension movement of the arm (highest differential of the test, 66.3°), not only due to the armour's articulation, but also due to the sewn mail defence on the arming doublet. However, even if the ROM in armour for this movement could have been greater with another type of fixation of the mail defence (estimated at 30°, pointing out one weakness of the version of the arming doublet replica used for this experiment), this particular movement would not have been useful in combat on the contrary, it would have exposed a weakness (the armpit), as outlined above. In the case of the flexion-extension of the elbow, the maximal extension was limited by the riveted elbow's defence (difference of 36.8°). Again, this constraint could actually have been beneficial, since it would prevent damage due to a pressure or an armlock (preventing muscle, joint or bone damage, as often described in the technical repertoire of the Fight Books).

Nevertheless, most of what can be defined as useful ranges of motion for combat situations was not limited by the armour. Furthermore, almost all maximal internal and external rotations were little constrained (see Tables 3 and 4), and even in some cases facilitated by the added weight which increased the particular ROM because of the inertial force parameter [16], as also observed for the gait analysis [17]. Noteworthy was the great trunk mobility due to functional articulation facilitated by tailor-made adjustments of the harness, allowing for example the subject to easily stand up from a lying position (Video 6). Our interpretation of the distinction between constrained and facilitated movements in armour is that it may have been designed intentionally and therefore should not be considered as uncontrolled consequences due to restrictions in material, technology or know-how of the artisans.

d. Limitations [subtitle 2nd level]

The main limitation of our study was the use of data gathered in a single male subject carrying one single specimen of harness. This should be confronted with the unique quality of the replica used, which was probably as faithful as possible to what was actually worn in medieval times (see Appendix 2). Ideally one would like to train several subjects, if possible with other accurate replicas of suits of armour of the same quality, representative of comparable typology for the end of the 15th c. for comparative studies. Indeed, it is not enough to just ask a number of subjects to wear armour and do certain movements. It takes training and therefore time to get used to wearing armour, and even more for learning the fighting movements as explained in the texts that we have studied. Our subject had several years of experience and was knowledgeable of the various moves and gestures in the studied Fight Books. Concerning the movement analysis, our results could be influenced by differences in markers' positions in and out of armour [18]. The markers, because attached to the armour, did not exactly represent the movement of the underlying joints – event though placed as closely as possible to the corresponding anatomic placement –, but that of the armour. But since our objective was to show any differences between ROMs of given movements, with and without armour, because of its potential impact on fighting movements, this does not invalidate our conclusions. Finally, any limitations imposed by the garment worn under the armour were not quantified separately. For instance, the mechanical characteristics of the textile and the mail defences (under the armpit and over the pelvis down to the knees) did seem to restrain several of the functional movements of both the lower and the upper limbs. In order to seize the impact of these factors, further research and experiments are needed. However, the lack of good documentary evidence and of material remains for those garments limits researchers to work according to a rigorous experimental archaeological process to reconstruct and to test the replicas [19].

Conclusion [subtitle]

We combined systematic analysis of a corpus of medieval texts with modern laboratory-based measurements using a faithful harness replica. The results of our experiments lead us to conclude that 1) the energy cost of walking is increased in excess of the added mass from wearing armour (66% vs. 46%); and 2) the armour's impact on the wearer's ranges of motion is rather limited. The weight is a relative impediment for proficiency of locomotion, but represents the price of higher protection. The impediment is comparable to that of the gear carried by a modern soldier or fireman. The excellent weight distribution over the body provided by a tailor-fitted harness replica and garment, a good physical condition and a proper training can therefore lead to respectable performances considering the added weight (46% of the body mass).

Concerning the armour's impact on the wearer's ranges of motion, it appeared that some movements were facilitated and some constrained by the armour, possibly connected to tactical dimensions for a combat situation. It can be that this embodied knowledge of armoured fighters represents a crucial, though unaddressed, element, tacitly taken into account by the authors of the Fight Books, who designed specific techniques exploiting these limitations to the advantage of the wearer. This hypothesis could enlighten comparative analysis between similar technical repertoires in Fight Books' sections for armoured and unarmoured fighting and would produce interesting data for the understanding of arms and armour. This area of research, supported by the results of this experiment demands further inquiries and tests.

Appendix 1: Fight Book corpus with armoured fighting techniques on foot, 1410-1510 [subtitle]

From the larger corpus of Fight Books encompassing 100 manuscripts and 30 prints dating from 1305-1570, we selected all known treatises dealing with armoured fighting techniques on foot for the chosen period (1410-1510). This selection includes specialised treatises discussing only armoured combat on foot, and also sections from treatises covering the three types of combat (without armour on foot, with armour on foot and on horseback). These witnesses deal mainly with longsword, but also discuss wrestling techniques, dagger, spear and poleaxe. The treatises sometimes include text only, sometimes only illustrations, or a combination of both media.

References are organised by author and title in chronological order, with philological tradition (manuscripts listed by their current location, in alphabetical order). Since authorial attribution is sometimes debatable, and titles are mostly non-existent, the incipit is added below. When the philological tradition is unfaithful, or when there are several archetypes, the most relevant are listed. All manuscripts and their content are analysed in the first volume of Jaquet (2013b: 125-249), codicological notices and secondary literature references are to be found in the second volume (Jaquet 2013b: 1-128). A publication by Brepols (coll. De Diversis Artibus) is in preparation.

Johannes Liechtenauer, [Zedel] (1389-1612)

Incipit: *Wer abesynnet vechtens czu fuße begyn̄et / Der schicke syn sper czwey sten am anheben rechte wer*

Manuscripts:

Augsburg, Universitätsbibliothek, Codex I.6.4°.3

Gotha, Forschungsbibliothek, Chart. A 558

Kraków, Biblioteka Jagiellońska, MS Germ. Quart. 2020

Roma, Biblioteca dell'Accademia Nazionale dei Lincei e Corsiniana, Codex 44.A.8

Salzburg, Universitätsbibliothek, MS M.I.29

Fiore dei Liberi, *Flos Duellatorum* (1400-1425)

Incipit: *Aquì comenza la spada de armizare. Ben serà magistro chi tali zoghi sarà fare. Gli magistri sono sie e zaschuno in guarda.*

Private collection, Pisani-Dossi MS

Los Angeles, Jean Paul Getty Museum, MS Ludwig XV 13

New York, Morgan Library, MS Morgan 383

Paris, Bibliothèque Nationale de France, MS Latin 11269

Varia, [glosses of Liechtenauer's Zedel] Kampffechten (1452-1570)

Incipit: *All hye hebt sich an die glos vnd die aus legūg der zedel der kunst des kampffechtens*

Dresden, Sächsische Landesbibliothek, Manuscripti Dresden C487

Glasgow, Glasgow Museums, MS E.1939.65.341

Kraków, Biblioteka Jagiellońska, MS Germ. Quart. 2020

Roma, Biblioteca dell'Accademia Nazionale dei Lincei e Corsiniana, Codex 44.A.8

Wien, Kunsthistorisches Museum, MS KK5126

Pseudo Fiore dei Liberi, [Fight Book] (1428-1510)

Incipit: *Io son sotana posta serpentina / Che de ferire de ponte son purpina*

Incipit: *Wer ein kampff soll fechten / der soll sein vortail suchen mit stant vnd vechten gen der sonnen*

Erlangen, Universitätsbibliothek, MS B.26

Roma, Biblioteca Nazionale Centrale, Codex 1324

Wien, Österreichische Nationalbibliothek, Codex 5278

Anonymous, Gladiatoria (1435-1500)

Incipit: *Merckcht den anfanckch des spiess wenn du zu dem ersten mal tritest in dye schrenck - vnd du ansichtig wirst deinen widertail*

Kraków, Biblioteka Jagiellońska, MS Germ. Quart. 16

New Haven, Yale Center for British Art, MS U860.F46. 1450

Paris, Musée National du Moyen Age, Cluny 23842

Wien, Kunsthistorisches Museum, MS KK5013

Wolfenbüttel, Herzog August-Bibliothek , Codex Guelf 78.2 August 2°

Anonymous, [Pseudo-Gladiatoria] (1420-1510)

Incipit: no text

Augsburg, Universitätsbibliothek, Codex I.6.4°.2

Berlin, Staatsbibliothek Preußischer Kulturbesitz, Libri picture A 83

Erlangen, Universitätsbibliothek, MS B.26

Paris, Musée National du Moyen Age, Cluny 23842

Wien, Kunsthistorisches Museum, MS KK5012

Wien, Österreichische Nationalbibliothek, Codex 11093

Wien, Österreichische Nationalbibliothek, Codex 5278

Wolfenbüttel, Herzog August-Bibliothek, Codex Guelf 78.2 August 2°

Hans Talhoffer, [Fight Book] (1448-1561)

Incipit: *Der Anfang des kampfs*

Gotha, Forschungsbibliothek, Chart. A 558

Königseggwald, Gräfliche Bibliothek, MS XIX.17-3

Berlin, Stiftung Preußischer Kulturbesitz, 78.A.15

København, Det Koneglige Bibliothek, MS Thott 290.2º

München, Bayerische Staatsbibliothek, Cod. Icon. 394a

Wien, Kunsthistorisches Museum, MS KK5342

André Liegnitzer, Das kurtz swert zu gewappenter hant (1450-1570)

Incipit: *Das erst stuck Item stich ÿm Inwendig zů seinē gesicht*

Augsburg, Universitätsbibliothek, Codex I.6.4°.3

Kraków, Biblioteka Jagiellońska, MS Germ. Quart. 2020

Roma, Biblioteca dell'Accademia Nazionale dei Lincei e Corsiniana, Codex 44.A.8

Salzburg, Universitätsbibliothek, MS M.I.29

Martin Hundsfeld, Das kurtz swert zu champf In harnasch aus vier huten (1450-1570)

Incipit: *Merck das ist die erst hůt Nÿm das swert in paid hend vnd schüt das krefftigcleich*

Augsburg, Universitätsbibliothek, Codex I.6.4°.3

Glasgow, Glasgow Museums, MS E.1939.65.341

Kraków, Biblioteka Jagiellońska, MS Germ. Quart. 2020

Roma, Biblioteca dell'Accademia Nazionale dei Lincei e Corsiniana, Codex 44.A.8

Salzburg, Universitätsbibliothek, MS M.I.29

Wien, Kunsthistorisches Museum, MS KK5126

Paulus Kal, [Fight Book] (1470-1515)

Incipit: *Allso schicke dich abezúsetzen wider schiessen*

Gotha, Forschungsbibliothek, MS Chart. B 1021

München, Bayerische Staatsbibliothek, CGM 1507

Solothurn, Zentralbibliothek, Codex S.554

Wien, Kunsthistorisches Museum, MS KK5126

Anonymous, *le Jeu de la Hache* (1460-1500)

Incipit: *Cy commence la doctrine et lindustrye du noble Jeu de la hache et la maniere de bataillier*

Paris, Bibliothèque Nationale de France, MS Français 1996

Anonymous, *Di accia armato di tutt'arme* (1480-1520)

Incipit: *Trovandoti contra al tuo nemico con l'Accia in mano in guarda alta, col piede manco innanzi*

Roma, Biblioteca Nazionale Centrale, MSS Ravenna M-345/346

Hans Folz, *Nota zu dem kampff* (1479)

Incipit: *Merck die 14 stuck mit dē / Swert vnd auch mit dem / Spicz swert degen vnd schilt / vnd gut kemflich ringē mit / dem degen*

Weimar, Nationale Forschungs- und Gedenkstätten der klassischen Deutschen Literatur, MS Q566

Appendix 2: Armour factsheet [subtitle]

This document outlines relevant information about the process of replicating historical armour and garments, and presents data about the replica used during the experiments.

Lack of material remains or documentary evidence and the impossibility of performing specific tests on remaining objects due to care and conservation reasons led to the necessity of manufacturing a replica for our study. Replicating objects in an archaeological experimental process implies choices and compromises that may have direct influence on the mechanical behaviour, ergonomics and visual aspects of the replica. Each of these choices and compromises based on the study of material remains, documentary sources and observations during experiments, have to be weighed according to the objectives and purposes of the experiments against pragmatic means (manufacturing, know-how, material, finance) according to the objectives and purposes of the enquiries and experiments. This leads to a circular process of identifying weaknesses or limits that might influence the mechanical behaviour, leading to an evaluation and then correction of the problem for a new cycle of observations (Lammers-Keijers 2005).

For our case, this process started with research in 2008, then manufacture of the replica in 2009, and the experiments analysed in this paper were performed in 2011 and 2012. The information and data here correspond to a snapshot of the still on-going process back in 2011-2012. The pursuit of realizing a replica that would correspond in all aspects with an historical object (material, manufacture, resistance, weight, visual aspect, mechanical behaviour, etc.) is an illusion. Several aspects have been researched and tested, others left aside as being irrelevant for the study or impossible to measure (lack of sources).

Imperatives, material and methods [subtitle 2nd level]

Four of the objectives that guided this project are listed below with their corresponding limits:

a. The replica must be representative of the harnesses depicted in the corpus of Fight Books (Appendix 1 and Figure 1).

Issue/limit: several typologies of defensive weaponry are depicted in this corpus, alongside with the technical evolution during the period (for illustrated treatises, 1448-1510). Archaeological remains already researched (published) or displayed in public collection do not have equivalents for all typologies depicted.

b. The replica must be based on archaeological remains (Figure 1)

Issue/limit: The different “armours” displayed in public collections are not always representative of an actual set of pieces worn together and the assemblage chosen may refer to a typology that might not match documentary or pictorial sources. Secondly, it is not an easy task even for professional researchers to have access to collections (public display or depot) trying to piece together different items to re-assemble a potential set of defensive weaponry that might have belonged together during a definite period of time, and representative of the typology researched.

c. The replica must be realized in an experimental archaeological manner (material and technology) and tailor-fitted to the subject.

Issue/limit: Know-how and finances are the most obvious issues. Then, all choices and selected compromises during production must be weighed against source material and projections/observations about mechanical behaviour of the end product. The cycles of experiments, observations and re-assessments lead to a never-ending endeavour tending to match an historical object, while this goal may never be achieved, mainly because of lack of source material.

d. The replica must be wearable upon a specific garment (arming doublet)

Issue/limit: Identical with most of the above-mentioned limits and issues, with the additional limit that even less source material is available.

Harness replica [subtitle 2nd level]

The model for the replica is the harness of Frederic I the Victorious, Count Palatine of the Rhine (1425-1476) and Prince Elector (1451-1476) (Jaquet 2013b: 297-302). It is kept at the Kunsthistorisches Museum in Vienna (inv. n. HJRK A2) and thought to date from 1451. According to Thomas and Gamber (1976: 56-58), it was made in at least three different Milanese workshops, most of them belonging to the Missaglia family (Williams 2003:96). It corresponded to some of the exigencies of the study and criteria mentioned above, since it is supposed to be an original assemblage of pieces belonging together and attributed to a historical character – though of a higher social status than most of the dedicatees of the Fight Books – and matching to some extent the typologies represented in the corpus. At the time of our research (2008), this piece was the best choice on the sample.

Qualified as field armour (Feldharnisch) by the institution, it shows characteristics of typologies meant to fight on foot, rather than on horseback, though on this set-up both are possible. The helmet of great bacinet type, the gauntlets and the symmetrical shoulder defenses are arguments in favour of foot combat and correspond to the typologies represented in the corpus, while the feet defenses (to avoid losing the stirrups), leg defenses without back plates (allowing the wearer to ride the horse) and the reinforced pieces covering the upper legs (meant for horse combat and jousting) would be arguments for the opposite. Three alterations have then been made when conceptualizing the replica to match Fight Books representations. We changed the solerets (feet defenses) for a model close to the ones kept in the Royal Armories in Leeds (Inv. N. III. 1348) dated from 1450; the gauntlets for a model similar to the ones kept in the Churburg Armory (Inv. N. 49) dated from 1475, without the decoration and shorter bavette and we decided to make symmetrical elbows' defenses, since the left reinforcing plate meant for jousting (absent on the original) does not correspond to the typology researched. Except for these alterations, the replica is a faithful copy of the functional aspects (see Table 5). Since visual aspects were not relevant for our study, features such as decoration (decorated rivets for examples) or armourer's marks have not been reproduced.

[here Table 5: Comparison between original and replica]

By studying and measuring the original, it appears that the mensuration of the original wearer were very close to the ones of our experimental subject. An overall increase of only 6% [20] was performed. The replica was made to measure with the subject wearing the arming doublet, compared and adapted to the measurement taken on the original piece and to the technical drawings (Boccia/Masserano 1982: 60, 79, 90, 105).

The raw material for the replica was sheets of medium carbon steel (0.3% C). All pieces were hand crafted with minimal use of heavy machinery, then put to heat treatment in a modern oven and quenched under supervision from Petr Brozek (professional armour craftsman since 2002). Finally the pieces were "mirror polished" both by hand and machinery. This finishing, corresponding to the original, is not meant for visual aspect, but both for care (less rust is likely to form on polished steel) and for defensive qualities (attacks by pointed weapons are likely to be deflected better on a polished surface). The end product is comparable, though relatively more resistant (uniform micro hardness [21]) than the original. However, resistance to aggression on the replica is not relevant for our enquiry, but weight and ergonomics of the replica are. Here we shall thank again the Foundation Ernst and Lucie Schmidheiny, who supported most of the project's cost.

Arming doublet replica [subtitle 2nd level]

Lack of remaining objects and pictorial sources have already been outlined (Capwell 2002). The most workable sources, though difficult to analyse, are both accounting documents and didactic literature (Jaquet 2013b: 304-315). During our research we experimented on four different versions of this type of garment, constantly re-assessing and correcting observed weaknesses. The two versions worn during the experiments of this paper are represented on Table 6.

[here Table 6: Arming doublet version 1 and 3
Legend: Top panel: Arming doublet (1st version) during demonstration for an exhibition at the National Museum of Middle Ages, Paris (2011); Drawing Gamber/Boccia (1972). Lower panel: Arming doublet (3rd version) during demonstration for a weapons' fair in Lausanne (2012); Drawing Gamber/Boccia (1972).]

Near the middle of the 15th c., innovations regarding harnesses became more stable and the garments worn underneath appear also to become more and more closely related to the civil pourpoint, though series of evidences can argue in favour of this trend dating from the second half of the 14th c. This type of garment, closely fitted and restraining the waistline, was realized in several layers of fabric, such as cotton, fustian, wool or even silk, with little padding, but quilted [22]. Arming points (knitted lace with a point) that allow pieces of armour to be laced onto it are added in several places, and mail gussets (mail defenses in different forms, see Capwell 2002; Pfaffenbichler 1992:56-60) are either sewn in or worn above, protecting the body areas where the harness articulates.

The third version of this replica worn for the second part of the experiment was realized with an inner layer of fustian, a construction layer of cotton, and an outer layer of silk (4 to 6 layers in total). Cotton padding was quilted onto the shoulders, the upper part of the torso (front), and the waistline. The 3rd and 4th version of the garment was tailored under expertise of Nicolas Baptiste (arms and armour scholar and costume experimenter). The mail voiders for armpits were constructed as half sleeves (corresponding to drawings of Gamber/Boccia (1972), see Table 6). The voiders for the pelvis and back of the upper legs were constructed as boxer shorts. The raw material for the mail defenses was a replica of mail defenses of iron with riveted flat rings of 8mm. diameter, manufactured in India and assembled by Youval Kuipers (Mailenkolder) in the Netherlands. The mail defenses weighing 4.3 kg (armpit, pelvis and back of the upper legs) were re-used for all four versions of the garment, with negligible weight variation due to the type and quantity of the fabric and threads used (total weight of version 1 to 4 of the arming doublet, including mail defenses, chausse, leather shoes and undergarments varied between 6.2 and 6.8 kg).

Notes [subtitle]

Acknowledgments: Conceived and designed the study: Jaquet in collaboration with Kayser, Armand and Bonnefoy-Mazure. Performed the literature analysis: Jaquet. Performed the experiments: Jaquet, Kayser, Armand, Bonnefoy-Mazure, Charbonnier and Ziltener. Analysed the data: Bonnefoy-Mazure and Armand (biomechanics) and Kayser (calorimetry). Contributed to the writing of the manuscript: Jaquet, Bonnefoy-Mazure and Kayser. Our recognition goes to the Foundation Ernst & Lucy Schmidheiny, who financed the harness replica and contributed to the expenses of the experiments.

1. Technical literature describing personal techniques of combat, for an introduction, see Boffa (2014). For a more detailed introduction and case studies, see Jaquet (2013).

2. *De armis defensibilibus aliquid est inscribendum que quo ad rationem tres principales partes expetunt hoc est quod in primis leuia sint tuta <et> exoluta. Quas q<ui>de<m> proprietates raro in armis videm<us>.* Pietro Monte, *Exercitiorum Atque Artis Militaris Collectanea,* Milano, Giovani Angelo Schinzenzler, 1509, book II, chap. 104.

3. About embodied knowledge and its connection with motor action, see for instance Sheets-Johnstone (2012), Tanaka (2011, 149-157) and Leigh Foster (2008, 46-59).

4. See the historiographical survey in Porter (2001) and in Cooter (2010). For a more comprehensive discussion, see for instance Bencard (2008 and 2009). About experiments with weapon replicas or martial gestures for inquiries related to Humanities problematics, see Jaquet/Baptiste (2015).

5. The experiments involved a single volunteer subject in good health (the first author) for low-risk routine non-invasive exercise testing in our accredited hospital based sports medicine

laboratory and image capturing in our movement analysis laboratory. The experiment was performed under umbrella permission from the local research ethics board for the collection of data during routine exercise testing according the principles of the Declaration of Helsinki.

6. For example, going further than the scarce measurements given by Blair (1958), detailed piece by piece measurements on suits of armour kept at the Wallace Collection (London) shows for the 15th c. weights ranging from 19 to 29kg (Capwell 2011). However, these weights were taken on suits of various types and without considering the added weight of the garment with mail defences. For more details on the weight discussion, see below under "Discussion" and Appendix 2.

7. *Kunst mit dem kurtzen swert zu champf In harnasch aus vier huten* (Rome, Accademia Nazionale dei Lincei e Corsiniana, Cod. 44 A 8, fol. 87r-90v). Edited by Hagedorn (2008:238-248). On the philological tradition and authorial attribution of this text, see Jaquet/Walczak (2014).

8. *Nÿm das swert in paid hend vnd schüt das krefftigcleich*. Ed. Hagedorn (2008:238).

9. Best described in the ms Wien, Kunsthistorisches Museum, KK5126, fol. 119r: "You should know where to look for openings on the armoured man or where you could best go through the harness. That is under the face or under the shoulders or in the hollow of the hand or on the arms behind the gloves or in the knee hollows or below to the soles of the feet and in the joints of the arm and between the legs and in the knowledge that his harness has joints you should thus seek the openings so that onward you need not work but stab when you next have one before you", translation of D. Jaquet. Ed. Lorbeer et al. (2009): *Dw solt gar ebenn wissenn an welichen stetenn an dem gewappeten man die ploss sold suechenn oder wo dw in durch denn harnasch am pesten mugst gewinen das ist vnder dem gesicht oder vnder yechsenn oder jn dem tener der hennt oder der paid arm jn denn handschuechen oder in dem gelennck der armpug oder in den chnie kellen oder vnden zw denn fussenn der solenn vnd*

zwischen denn pain vnd in allenn gelidenn des harnasch vnd die ploss sold dw also recht suechen das dw einer feren nit sold zw stechenn wenn dw ein nachnere vor dir hast.

10. The main characteristics are small foot defence, protection of the back of the legs, head defence without neck articulation, descending pelvis defence. Some of the Fight Books would show more classical typologies allowing both fighting on foot and on horseback lacking specific pieces, but are statistically exceptions. For a more detailed analysis, see the article of Baptiste in Jaquet (2013a:121-152).

11. *kunst die vnder halden vnd die auf sten Im harnasch zu kampf* (Rome, Accademia Nazionale dei Lincei e Corsiniana, Cod. 44 A 8, fol. 90r). On the philological tradition and authorial attribution of this text, see note 5. Enactment of a knight standing up wearing original armour was already filmed in 1920s under supervision by Metropolitan Museum curator and assistant curators, see Dean B, Grancsay SV, Hoopes TT (1924) A visit to the Armor Galleries. Short movie, Metropolitan Museum, New-York. Available: <http://www.metmuseum.org/metmedia/video/collections/aa/visit-to-armor-galleries>. Accessed 29 March 2014. Standing up in armour scene: 11:30.

12. According to chronicles and relation of chivalric games (see for examples cases studies outlined in Gaier (1985-1986), but also according to normative literature related to heralds' function, see for instance Hiltmann (2011).

13. See footnote 9 (Wien, Kunsthistorisches Museum, KK 5126, fol. 119v).

14. Based on case studies conducted on preserved suits of armours of the fifteenth up to the first decades of the sixteenth centuries, armours can weigh between 18kg up to 40kg, see Blair (1958:156). The average for a complete harness in the fifteenth century would be between 20 to 26kg, as shown by piece-by-piece measurements done on selected objects of the Wallace collection. However, those weighing were done without considering the added weight of the garments and the arming doublet. Thus, the overall weight of the harness,

arming doublet (incl. mail defences), chausses and shoes (39.8kg) is not so surprising compared to the weight of a field armour, if the weight of the undergarments (6.6 kg) is subtracted and if the bacinet is exchanged for a sallet (minus 3 kg), amongst other possible combinations.

15. The replicas worn were based on designs of the second half of the fifteenth century (for the majority last decades) and of a typology that does not match an armoured men-at-arms involved in the battles of Crecy (1346) and Agincourt (1415). It is also difficult to argue about weight of armour for this period, at least not based on objects (no complete sets preserved). For remarks to the weight of the equipment of men-at-arms, see DeVries and Smith (2012:85-86) and Nicholson (2004:109). Regarding the issue of standing up in armour, see Breiding (2010) and Video 6.

16. Adduction of the shoulder measured at negative differential of 0.46° (see Table 4).

17. Rotation of the left hip with a negative differential of 18.73° (see Table 2).

18. The passive markers used are usually placed directly on the skin. Since these could not be placed under the armour (reflective action), they have been placed upon, as close to the articulation as possible. This may have added minimal imprecision to some of the measurement, compared to placement on the skin.

19. The reconstruction of the arming doublet worn during these experiments was the third version, more information on Appendix 2. Concerning the lack of material available to study, see Capwell (2002). For a discussion about archaeological experimental methods, see Lammers-Keijsers (2005).

20. These measures were taken on anatomical points on the armoured pieces, such as wrist to elbow, ankle to knee and so on. The fact that the armour goes over the members on a garment leave a margin of error for anatomical measurements.

21. Our only data for comparison was the archaeomettalurgical investigation made by Williams (2003) on the left cuisse of the original (see Table 5). Though these data are not strictly representative of all pieces, they were the only available.

22. For case studies about the Burgundian court, based on accounting document, see for instance Jolivet (2003: 102-108). For details about fabric and construction, see also the well-known anonymous didactic text "How should a man be armyd", referenced and commented in Lester (1984:84-85).

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Video 1. Sample of the test of energy expenditure on treadmill in armour. Taken at Laboratoire de l'Unité d'Orthopédie et de Traumatologie du Sport, Genève (10.08.2011). Online: https://mediaserver.unige.ch/play/90867.

Video 2. Sample of the gait analysis in armour. Taken at Artanim Foundation, Geneva (21.03.2012). Online: https://mediaserver.unige.ch/play/90868.

Video 3. Sample of the functional movement test out of armour. Taken at Laboratoire de Cinésiologie Willy Taillard, Hôpitaux Universitaire de Genève (13.04.2012). Online: https://mediaserver.unige.ch/play/90869

Video 4. Sample of the functional movement test in armour. Taken at Artanim Foundation, Geneva (21.03.2012). Online: https://mediaserver.unige.ch/play/90870.

Video 5. Motion capture of a knight in armor. Short movie for a blogpost, realized by Artanim Foundation (2012). Online: https://mediaserver.unige.ch/play/90871.

Video 6. Combattre en armure au XVe siècle: Approche expérimentale avec équipement reconstitué et étude des traités de combat. Short movie realized for the exhibition “L’Epée. Usages, mythes et symboles” at the National Museum for Middle Ages in Paris (2011). https://mediaserver.unige.ch/play/90872.

Table 1: Action verbs for offensive actions in "Shortened sword from the four guards"

Action verb	**Action's description**	**Action in context**
Set the point in *ansetzen* 41 occurrences	Action consisting of placing the point in one of the harness' weaknesses. This action does not necessarily end with a penetration of the blade into the adverse body.	Note everything you will set the point to: in the face, in the throat, in the left shoulder or in the armpit and thus rush in. *Merck alles das du wil an setzen das* [89r] *setz an an das gesicht oder an die drossel oder an die linck achsel oder vnder die vchsen vnd dring in also*
Thrust/stab *stechen/stich* 26 occurrences	Action consisting of pushing the point (or other parts of the sword such as the cross) into weakness of the harness. This verb is used as a noun in 10 occurences.	Or if he has turned his hand around on the blade, then thrust him above in the fingers and lift out upward. [89v] *Item ob er die hant hat vmb gewant auf der klingen so stich in oben in die finger vnd heb vber sich auf*
Retrieve *zucken* 2 occurrences	Action consisting of pulling back the sword after a defensive action of the adversary	"[…] if he defends, then retrieve and go through with your thrust and set him the point as before." [87r] […] *wert ers so zuck vnd gee durch mit tem stich vnd setz Im an als vor.*
Strike *s[ch]lahen/ s[ch]lach* 11 occurrences	Action always executed with specific parts of the sword: 9x with the pommel on the adversary; 2x with the handle under the armpit (as a lance for a jouster). This verb is used as a noun in 1 occurrence.	"Or strike him with the pommel on his forward driven elbow." [88v] *Oder slach Im zuo mit dem knopf zuo dem vorgesatzten elpogen*
Push *stossen/drucken/ dringen* 15 occurrences	Action executed with or without the sword, mainly in order to throw the adversary or exercising a lock. *dringen* is used 3 times to mention thrusting with the sword.	"Take the pommel well with your left hand and push him the sword behind back and thrust him in the testes" [88r] *Nym des klosses war mit der lincken hant vnd stos Im das swert hinder ruck vnd stich vnden zuo den hoden*
Pull *anrucken/zeuchen* 6 occurrences	Action executed with or without the sword, mainly in order to throw the adversary or exercising a lock.	"When you displace then drive above with the handle over his forward driven handle and pull it to you and counter-attack and set the point." [87r] *Item wenn du vor setzt so var vber mit der hanthab vber sein vor gesatztew hanthab vnd zeuch zuo dir vnd prich vnd setz an*

Manuscript of reference Rome, Accademia Nazionale dei Lincei e Corsiniana, Cod. 44 A 8, fol. 87r-90v. Edition Hagedorn (2008: 238-248). English translation Jaquet.

Table 2: Range of motion of the joints during the gait cycle without and with armour.

	ROM during walking (°)				
	Ankle - Flexion/Extension	**Knee - Flexion/Extension**	**Hip - Flexion/Extension**	**Pelvis - Tilt**	**Trunk - Tilt**
Without armour	29.0 (1.8)	58.1 (0.8)	38.8 (1.6)	2.5 (0.6)	2.6 (0.9)
With armour	40.0 (1.7)	59.0 (1.6)	38.0 (1.3)	2.9 (0.6)	3.0 (0.7)

Range of motion (ROM - in degree (°)) during the gait cycle for the: ankle, knee, hip, pelvis and trunk joints in the sagittal plane (flexion/extension movement and tilt movement). The data corresponds as the mean values calculated for a minimum of gait cycle with standard deviation (in parenthesis).

Table 3: Range of motion of the lower limb joints during maximal functional movements without and with armour.

Maximal functional movement	ROM (°)	STD	DIFF (°)
HIP			
Flex/Ext without armour	98.6	1.6	23.2
Flex/Ext with armour	75.4	2.3	
Flex/Ext without armour and with knee flexed	92.8	2.5	20.3
Flex/Ext with armour and with knee flexed	72.5	3.1	
Abd/Add without armour	59.9	2.9	29.9
Abd/Add with armour	30.0	1.6	
RI/ RE without armour	25.8	0.7	-1.8
RI/ RE with armour	27.6	2.0	
KNEE			
Flex/Ext without armour	129.8	2.4	30.3
Flex/Ext witharmour	99.5	2.3	
RI/ RE without armour	28.1	2.5	7
RI/ RE with armour	21.1	2.3	
ANKLE			
Flex/Ext without armour	64.2	3.4	-5.5
Flex/Ext with armour	69.7	1.8	

Range of motion (ROM) and standard deviation (STD) of: hip, knee and ankle joints during specific maximal functional movement without and with armour. Flexion – Extension: Flex/Ext; Abduction – Adduction: Abd/Add; Internal and external rotation: RI / RE.

Table 4: Range of motion of the upper limb joints during maximal functional movements without and with armour.

Maximal functional movement	ROM (°)	STD	DIFF (°)
TRUNK			
Bending without armour	61.4	0.4	2.3
Bending with armour	59.1	2.8	
Rotation without armour	80.6	6.9	8.1
Rotation with armour	72.5	7.9	
SHOULDER			
Flex without armour	128.3	2.6	66.3
Flex with armour	62.0	2.1	
Ext without armour	34.5	3.3	17.7
Ext with armour	16.8	1.8	
Add without armour	14.3	2.9	-0.5
Add with armour	14.8	4.2	
Abd without armour	149.2	1.7	64.9
Abd with armour	84.3	2.8	
RI/RE without armour	129.5	2.6	6
RI/RE with armour	123.5	2.7	
ELBOW			
Flex/Ext without armour	109.1	0.5	36.7
Flex/Ext with armour	72.4	0.9	
WRIST			
Flex without armour	28.6	1.3	21.4
Flex with armour	7.2	0.8	
Ext without armour	23.5	2.7	12.1
Ext with armour	11.4	1.9	

Range of motion (ROM) and standard deviation (STD) for trunk, arm, elbow, and wrist during specific maximal functional movement without and with armour. Flexion – Extension: Flex/Ext; Abduction – Adduction: Abd/Add; Internal and external rotation: RI/RE.

Table 5: Comparison between original and replica

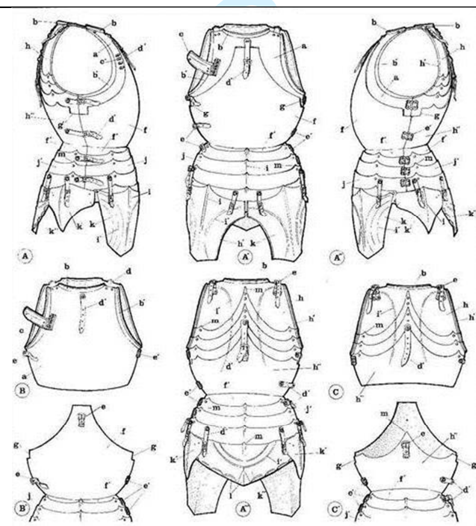
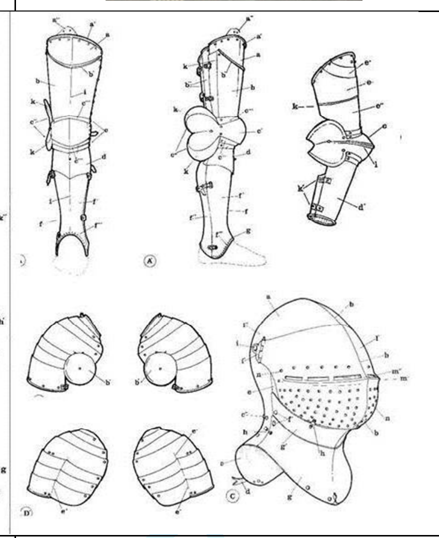
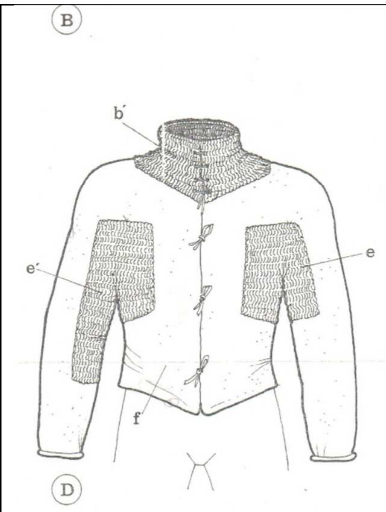
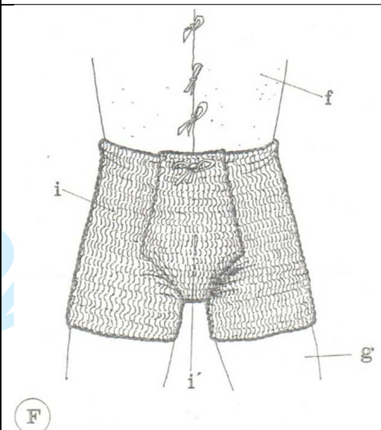
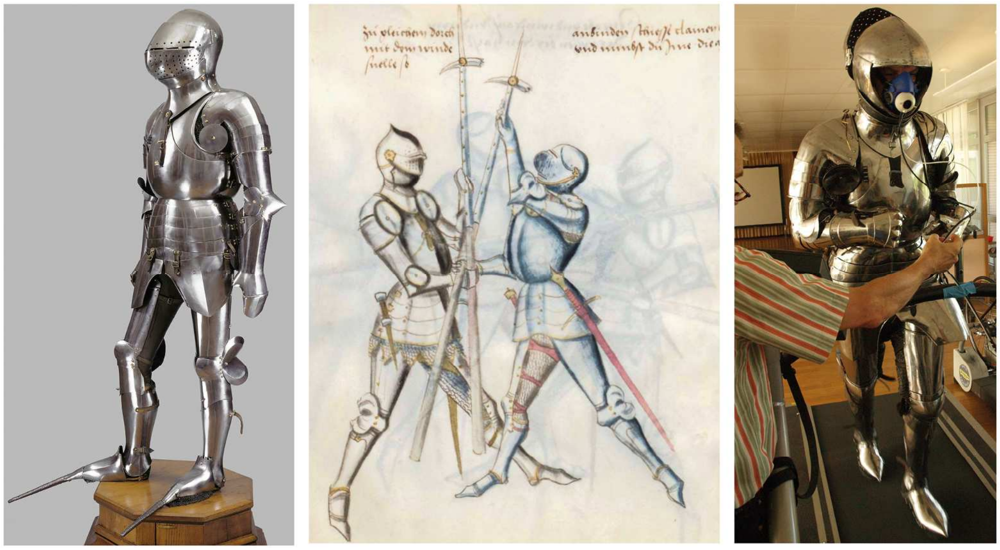
	Original	**Replica**
Picture (credits see Figure 1 of the main article)		
Technical drawing		
Height	189 cm (measured on display)	192 cm (measured worn)
Weight	32180 gr (measured by museum staff)	33090 gr (measured in laboratory)
Material	Low carbon steel (ca. 0.2%C) (measured on the left cuisse)	Medium carbon steel (0.3%C) (all pieces)
Heat treatment	Some form of quenching (estimated on the left cuisse)	Quenched (all pieces)
Micro hardness	(average) 226 VPH (measured on the left cuisse)	Not measured (irrelevant for this study)

Table 6: Arming doublet version 1 and 3

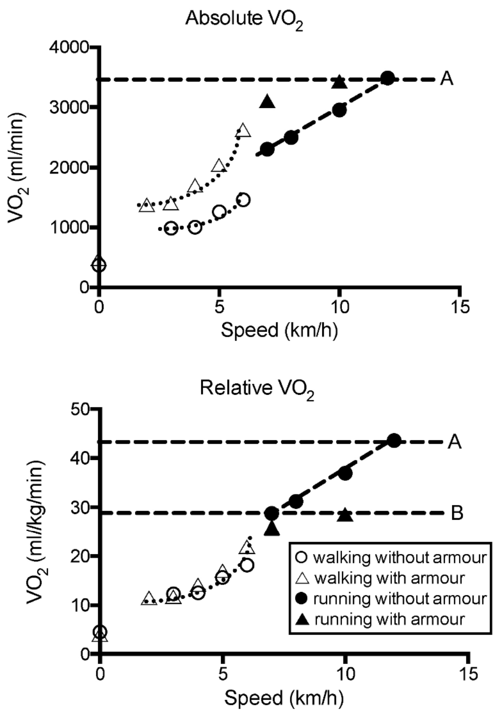




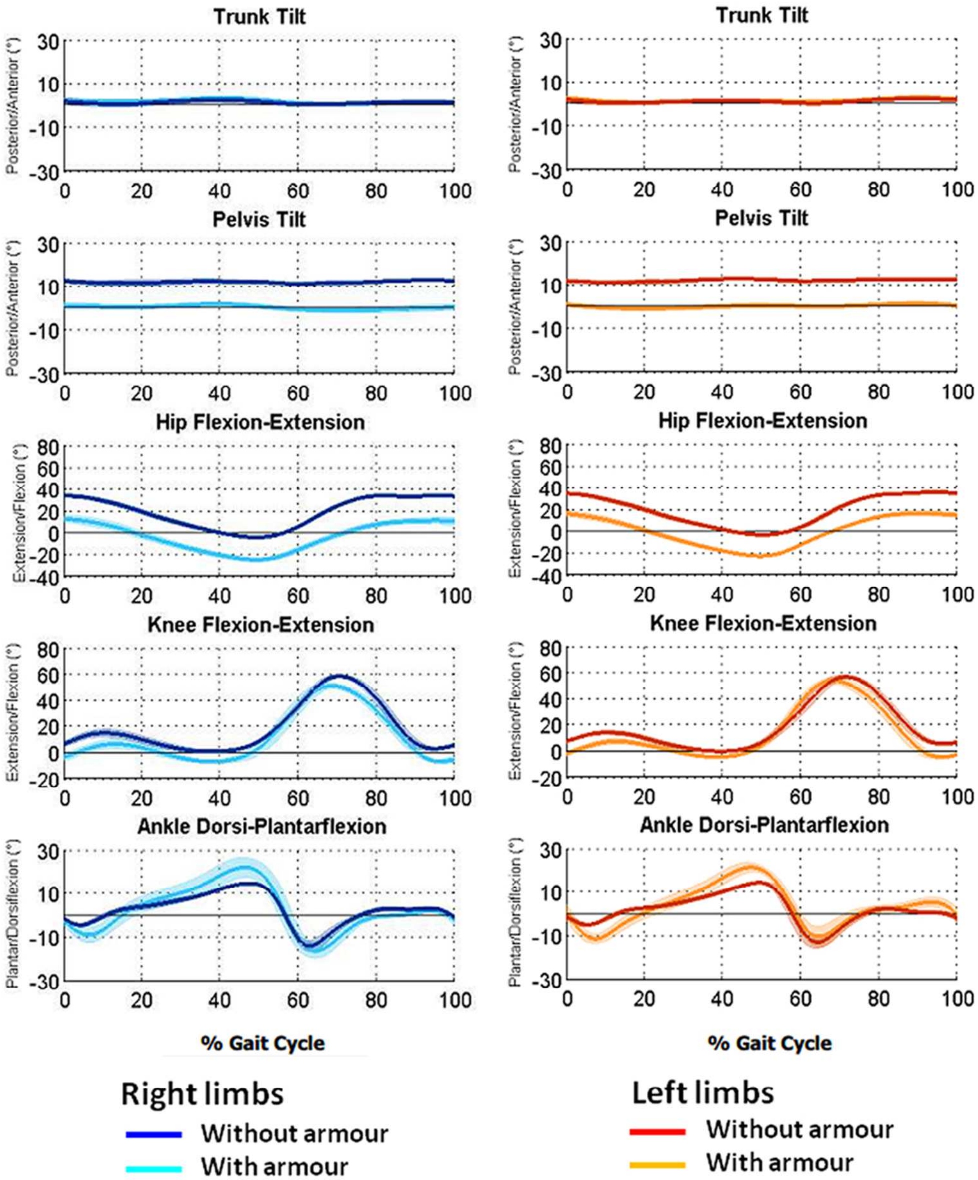
Legend: Top panel: Arming doublet (1st version) during demonstration for an exhibition at the National Museum of Middle Ages, Paris (2011); Drawing Gamber/Boccia (1972). Lower panel: Arming doublet (3rd version) during demonstration for a weapons' fair in Lausanne (2012); Drawing Gamber/Boccia (1972).



Caption: Comparison between the original suit of armour, the representation of its typology within the Fight Books' corpus and the replica worn for the experiments.
Legend: Left panel: Suit of armour of Frederick Ist, steel and leather, several Milanese workshops, ca. 1450, © Wien, Kunsthistorisches Museum, Hofjagd- und Rüstkammer, Inv.-Nr. A 2. Center panel: Representation of a pair of armoured fighters in Paulus Kal's Fight Book (1459-1479), Paper, © München, Bayerische Staatsbibliothek, Cgm 1507. Right panel: Replica, steel and leather, photo by E. Jaquet
199x109mm (300 x 300 DPI)



Caption: Oxygen consumption during walking and running with and without armour.
Legend: Top panel, absolute oxygen consumption, which reached maximum aerobic capacity in both instances (with and without armour), as indicated by line A. Bottom panel, relative values normalized for body mass with and without armour. Line A represents relative aerobic capacity normalized with body mass and line B with mass of the armour added.
209x297mm (300 x 300 DPI)



Title: Joint kinematics, in the sagittal plane, of the lower limbs and trunk during the gait with and without armour.
Legend: The two columns present the kinematic curves (in degrees) obtained for the subject in the sagittal plane for the right limbs in blue (without armour) and cian (with armour) and for the left limb in red (without armour) and orange (with armour). The vertical lines indicate the end of the stance phase. Positive angles indicate a dorsiflexion of the ankle, a flexion of the hip and knee, and an anterior movement of the pelvis and trunk.
80x96mm (300 x 300 DPI)