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Wood Chippers: Influence of Feed Channel Geometry on Possibility of Musculoskeletal System Overload

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Abstract

The position and shape of the feed channel (FC) in low-power woodchippers significantly affect the way machine operators' upper limbs move. The execution of operator's movements can be accomplished in different working areas: comfortable, acceptable, or not recommended due to overloads in the musculoskeletal system. Three groups of male subjects from Central Europe, divided according to anthropometric dimensions from centile groups C5, C50 and C95, were selected to assess upper limb movement, by adopting a Motion Capture measurement method. The tests have shown that the limb closer to the FC (left hand in this study) carries out all the movements in the allowed zone (AZ), while between 79% and 96% of the limb movement is contained within the comfort zone (CZ). The right limb has a greater amplitude of motion outside the CZ working area – from 0% to 69% and for AZ – in the CZ can vary by up to 51%. It was found that commercial low-power woodchippers deployed in urban areas, typically induce overloads in the musculoskeletal system of the operator during the use. Based on the research results, the authors see the need to improve FC position adjustment for the operators of these machines.

Keywords: low-power woodchippers, musculoskeletal loads, manual feeding, feed channel, upper-limb movement analysis

1. Introduction

Maintenance of urban trees requires a reduction of residues produced regardless of their destination – energy or composting or even bio compounds (Grohmann et al. 2019) for transport and logistics reasons. Clearly, every part of the tree can be comminuted: branches, trunks (Preethi et al. 2019), roots (McEwan et al. 2019) or the whole shrub or tree (Mitchell and Gallagher 2007). According to the impurities potentially present in the raw material such as stones, metallic objects, etc., a different machine will be chosen, usually a grinder for contaminated material or a woodchipper for uncontaminated material. Size and shape of wood chips is of great importance for the resulting products, e.g., solid biofuels, liquid fuels, gaseous fuels (Manouchehrinejad et al. 2018, Moskalik and Gendek 2019, Sirisomboon et al. 2020), since the particle size distribution makes them falling in one commercial category or another (EN ISO 17225 1:2021) depending on the sharpness of the chipper blades and on the type of screen used (Nati et al. 2010, Nati et al. 2014).

Chippers can be classified by their power, configuration (tractor-powered, towed or self-propelled), or by the feeding method (manual or mechanic) (Spinelli and Hartsough 2001). High productive chippers have a high power, commonly about 250–840 kW (Nati et al. 2010, Spinelli et al. 2011, Han et al. 2015, Spinelli et al. 2016, Irdla et al. 2017). They are fed by grapples and cranes, and built in the chipper itself or in other machines as loaders (Nati et al. 2014, Ghaffariyan et al. 2012, Laitila and Routa 2015, Spinelli et al. 2020, Spinelli et al. 2017, Mihelič et al. 2018). The literature also contains studies regarding less powerful chippers (ranging 63–230 kW), fed through manual or mechanized methods (Spinelli et al. 2015, Choi et al. 2019, Kormanek 2020, Suardi et al. 2020). A group of chippers with a power <19 kW is also available on the market (Warguła et al. 2020a, 2020b, 2022a), designed for treating small size residues. This specific category of small comminuting machines (chippers and grinding) is defined by the European Union as non-road spark ignition (NRSh) mobile machinery, exclusively for use in hand-held mode, regulated by the European Parliament and the Commission on requirements affecting gaseous and particulate pollutant emission limits (EU No 2016/1628). The spark ignition (SI) engines installed in the »19 kW group« define the name of the driving unit as a »small engine«. Based on that, the authors believe that the group of comminuting machines equipped with such independent engines should be called »low-power chippers« (Waluś et al. 2018, Warguła et al. 2022b). Such machines are most used in urban areas or forest areas with difficult access, specifically for small trees or pruning, when feeding is handled manually (Bagagiolo et al. 2017, Colantoni et al. 2017, Cremasco et al. 2019, Warguła et al. 2020b). The comminution of residues coming from the maintenance of green areas, home gardens, and roadside areas facilitate the transport and storage of wood biomass (Warguła et al. 2022a, 2022b).

The operators of such machines are exposed to several hazards, e.g., injury (Zhu and Gelberg 2018), noise and vibration (Rottensteiner et al. 2013, Krolczyk et al. 2014, Poje et al. 2018a, 2018b, Cremasco et al. 2019), harmful combustion gases (Manzone 2015, Warguła et al. 2020e) and dust (Magagnotti et al. 2013, Gulci et al. 2018). In 2015, Poje et al. found that diesel engines of wood chipping machines are the main source of noise both in forestry and in agricultural residues recovery, but the level of this noise affecting the operators does not exceed 80 dB(A) (Poje et al. 2015). Studies on this topic were also conducted by Camargo et al. in 2021. They show that noise levels were in the range of 80 dB(A) to 85 dB(A), exceeding the permissible limits of noise exposure adopted by the labour law in the country where the study was conducted (Brazil) (Camargo et al. 2021). Exceeding the permissible limits was also found by Cremasco et al. (2019), after investigating the risk of musculoskeletal disorders in operations involving manual feeding of wood to a woodchipper (Cremasco et al. 2019). The paper analyzed machines with a horizontal feed channel driven by a 55-kW tractor, and used RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) for analysis, showing that the operator is exposed to biomechanical overloads during manual feeding operations, and that manual loading systems for wood chippers need further research and development (Cremasco et al. 2019).

Among the numerous research analyzing the principles of workplace ergonomics and musculoskeletal loads for wood chipper operators, there is a study by Gejdoš et al. 2021, who related the operator size to the machine used, e.g. loaders for chipper feeding. The Authors concluded that this is a very important aspect in the design of these machines, because it improves the comfort of operators, but also their safety and occupational health (Gejdoš et al. 2021). However, the changes in the feed channel of comminuting machines in recent years mainly concerned safety systems (e.g. the chipper shutdown in emergency situations) as stated by Bagagiolo et al. 2017, or wood detection mechanism in the feed channel, to reduce the machine cost during idle time (Warguła et al. 2020c, 2020d, 2020f).

The literature review conducted by the Authors on the ergonomic aspects involving chippers operators indicates that this type of workers are subjected to many adverse factors such as noise, vibration, and polluted air. In addition, they must exercise extreme caution when acting closely to cutting tools. Another risk for operators' health is biomechanical overload in the body. Ergonomic design of the operator's machine cab or a favorable placement of the chipper's feed channel (Cremasco et al. 2019) are crucial for the well-being of the operator (Gejdoš et al. 2021) and can contribute to better working conditions. Based on this, the Authors decided to conduct a study on low-power woodchippers, which are fed manually. Four machines commonly used in urban areas characterized by different feed channel geometries were selected. This paper presents the range of movement of the upper limbs of the operators during wood feeding to a woodchipper in relation to limb movement zones: comfort zone (CZ) and allowed zone (AZ). A Motion Capture measurement method was applied to analyze upper limb movement – as an innovative application of this technology. The aim of the article is to investigate the working conditions of low-power manually-fed woodchippers, to reduce risks of overloads in the operators' musculoskeletal system and to provide indications and guidelines for manufacturers.

2. Materials and Methods

Four woodchippers, commonly used in urban areas to dispose of green maintenance of houses, roads, or parks, were analyzed. The common feature of the machines was a power of approx. 10 kW. Drive units of this power are classified in the European Union (EU No 2016/1628, Waluś et al. 2018, Warguła et al. 2022b) as NRSh. The four chippers analyzed differed in the design of the cutting system, which affects wood feeding mechanism. Warguła et al. studied such machines in terms of energy consumption and productivity, hence a detailed description of these machines is avail-

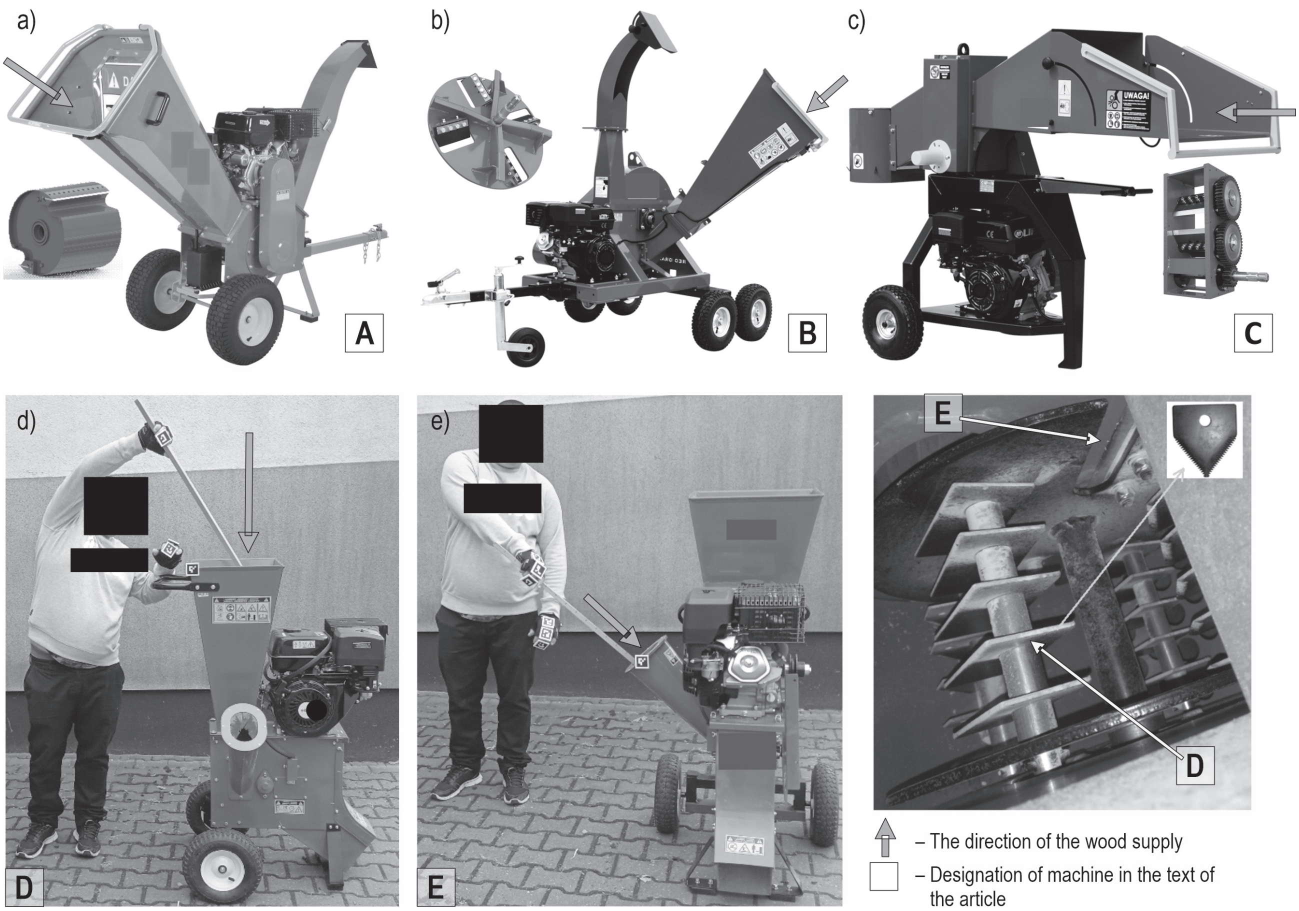

Fig. 1 Wood chippers with different cutting systems, where: (a) drum (A), (b) disc (B), (c) two-cylinder (C), (d) flail (D), (e) disc (E)

able in their paper (Warguła et al. 2022a). The four wood chippers, featured by different feeding systems are shown in Fig. 1: drum (A), disc (B), two-cylinder (C) plus a model with two cutting systems: flail (D) and disc (E). The characteristics of the machines are presented in Table 1.

The ergonomics for chippers feeding was evaluated by employing three male builds, typical of the Central European population. The selection of machine operators and their classification were adopted from the anthropometric atlas, conceived for the evaluation of design and ergonomics of machines (Gadliczak 2001). A male sample corresponding to the group of anthropometric dimensions in centiles: C5, C50 and C95 was selected for the study, corresponding to small, medium-sized, and large men. The height of the user sat in the Frankfurt plane (standard position of the head or skull used in physical anthropology) measured from the ground to the vertex point on the surface of the skull is as follows: C5 is 164.3 cm, C50 is 174.8 cm, and C95 is 185.4 cm. The length of the upper limb measured from the shoulder girdle to the center of the clenched fist is as follows: C5 is 73.6 cm, C50 is 78.3 cm, and C95 is 82.6 cm (Gadliczak 2001). According to human measures and mobility range of the upper limb kinematic chain, three work zones were established: the comfort work zone (CZ), corresponding to the preferred width of the work zone, the acceptable zone (AZ), corresponding to the maximum width of the work zone, and the non-recommended zone, which is the area beyond the maximum width of the work zone (Gadliczak 2001) (Fig. 2). Zone range values corresponding to the width (B1 and B2) and height of the ellipse (A1 and A2) for the selected male size are shown in Table 2.

The article focuses on the ergonomics of upper limbs manipulation area. Markers placed on the hand depicted the actual hand displacement, thus indicating the area in which manipulation occurs during delivering wood to the wood chipper. Of course, other body segments also move, however, crucial for analyzing the device ergonomics is the final hand position. This position is dependent on the movement of body segments

Table 1 Characteristics of woodchippers

Type of cutting mechanism	Drum, A	Disc, B	Two-cylinder, C	Wood size reduction machines with two cutting mechanisms	
				Flail, D	Disc, E
Manufacturer	HECHT MOTORS, s.r.o., Mukařově – Tehovci, Czech Republic	Remet CNC Technology Sp. Z O.O., Kamień, Poland	Remet CNC Technology Sp. Z O.O. Kamień, Poland	HECHT MOTORS, s.r.o., Mukařově – Tehovci, Czech Republic	
Model	HECHT 6642	RTS-630	Red Dragon RS-100	HECHT 6421	
Number of knives	2 knives per drum and 1 counter blade	4 knives per disc and 1 counter blade	4 knives (2 knives on one shaft)	20 knives (5 knives on one shaft)	2 knives per disc and 1 counter blade
Recommended drive unit power	10 kW	10 kW	10 kW	10 kW	10 kW
Manufacturer's recommended maximum wood cutting diameter: Fresh softwood/Fresh hardwood/ Dry hardwood	–/–/100 mm	100 mm/80 mm/60 mm	80 mm/70 mm/60 mm	–/–/10 mm	–/–/90 mm
The height of the bottom wall of the feed channel from the ground	1110 mm	1130 mm	850 mm	1330 mm	690 mm

preceding the hand. In the conducted study, the kinematic chain examined was foot, shin, thigh, torso, shoulder girdle, arm, forearm, hand with a marker.

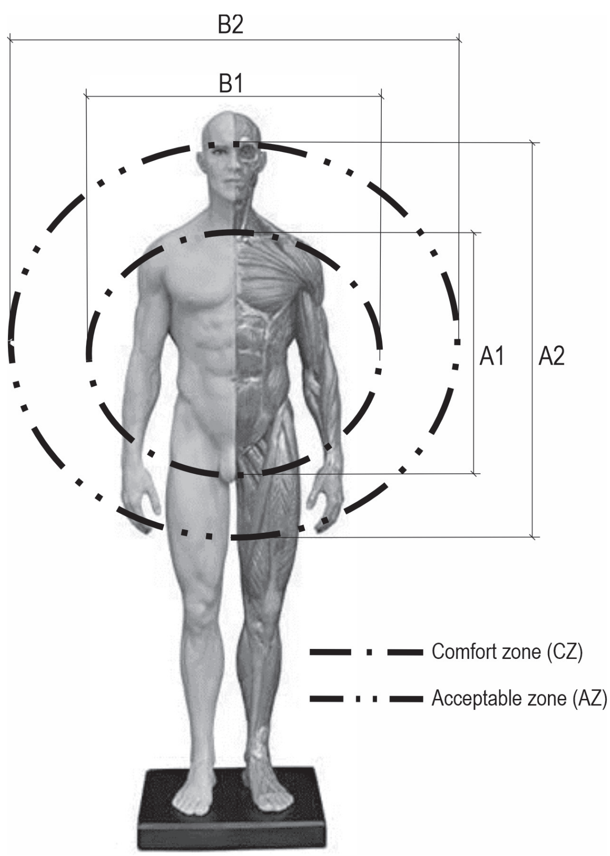

Fig. 2 Working areas in frontal plane

Recording the positions of segments preceding the hand is unnecessary for the research objective.

To standardize the working conditions, beams 1 m long and 10x10 mm cross-section wide were used to feed the machine. The analysis of the movement started when the operator was holding the piece of wood with both hands (roughly above the knee, below the waist, Fig. 3a). The Authors assumed that the movement of reaching for the wood was the same for all the machines (therefore not subject to analysis). During the feeding stage, the main movement was in the frontal plane, hence the motion factor in this plane was carefully analyzed (Fig. 3b – final phase of movement). The system for recording the hand position consisted of a GoPro HERO 7 camera (Fig. 3c) and an illuminating lamp (Fig. 3d) that were in a fixed and stationary position relative to the test subject. Both elements were placed on a tripod. The operator under test was equipped with sensors attached to the hands (Fig. 3e), while the test machine was equipped with a stationary ID0 marker against which the movement of the sensors

Table 2 Values of comfort (CZ) and acceptable (AZ) work zone dimensions according to male size

Male size		C5	C50	C95
Preferred work zone height, mm	A1	388	405	416
Maximum work zone height, mm	A2	865	893	937
Preferred work zone width, mm	B1	435	453	469
Maximum work zone width, mm	B2	742	805	861

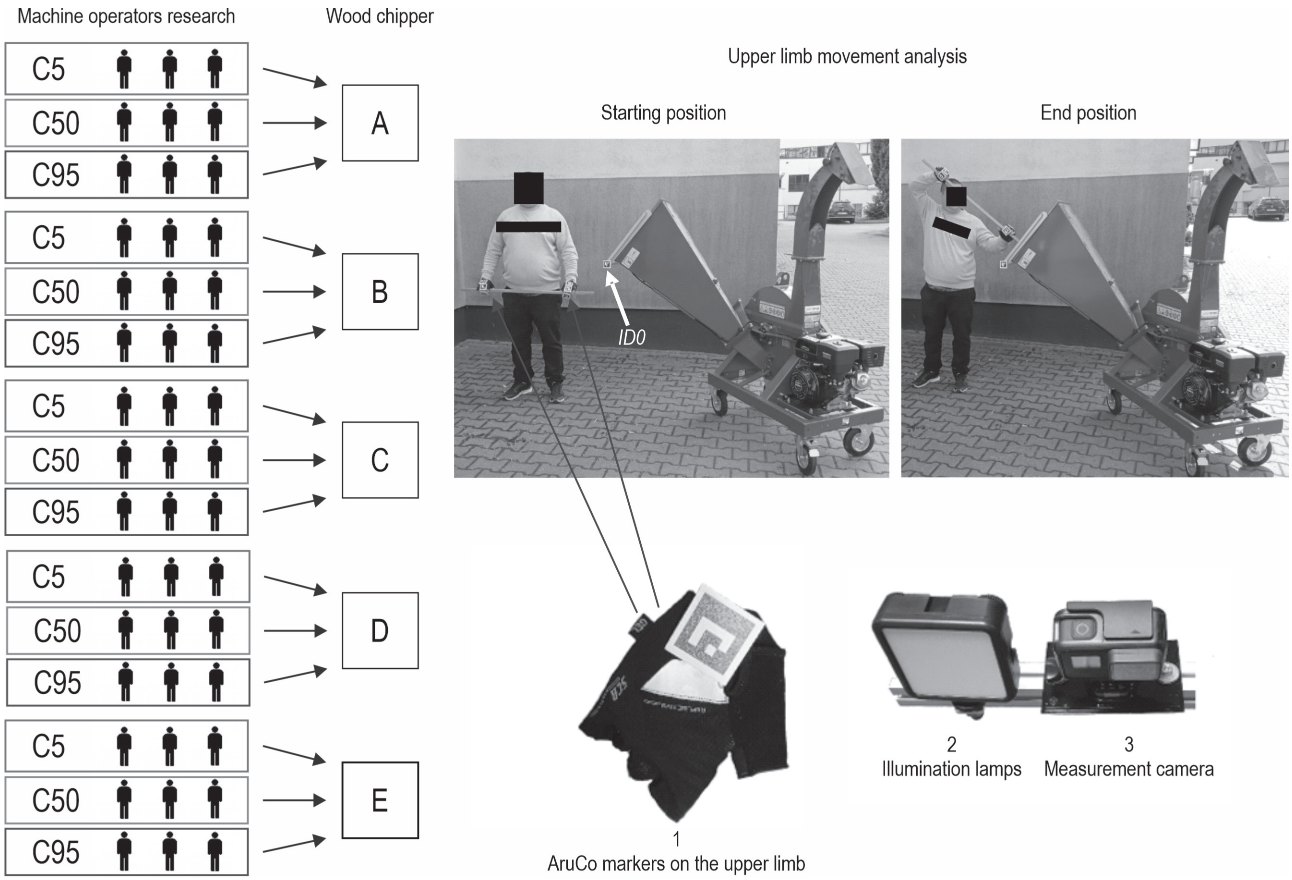

Fig. 3 Measurement equipment and conditions

applied to operator's hands was analyzed. The camera captured 960p (the number 960 means a vertical screen resolution of 960 horizontal lines, and the letter «*p*» means progressive or non-interlaced) video at 75.152 m/s. The illumination lamp, on the other hand, provided 200 to 1000 lumens, depending on the intensity of the ambient light. AruCo codes printed on 50 mm by 50 mm plates were used as markers (Kulyukin and Mukherjee 2019, Wieczorek et al. 2020).

The comparison between Motion Capture methods utilizing AruCo markers with a single camera and methods employing markers on clothes and at least two cameras along with additional lighting has been extensively discussed in numerous scientific publications (Wieczorek et al. 2020, Metzner et al. 2020, Yaldiz et al. 2022). However, for studying the movements of wood chipper operators, the Motion Capture method with AruCo markers and a single camera was chosen. This decision was primarily due to the fact that such studies are often conducted in open spaces, where emissions of exhaust gases and dust are possible during machine operation. Methods involving work clothes require a studio setup with a large number of cameras and precise lighting to minimize shadows and ensure high contrast between the background and the markers on the clothes, regardless of whether they are active (with LED lights) or passive (without LED lights). Using passive markers with AruCo codes allowed measurements to be taken with just one camera. Additionally, active markers with LED lights are sensitive to strong sunlight, which can interfere with data registration. The method of measurement utilizing clothes with accelerometers is an intermediate method, introducing additional errors due to the integration of accelerations, unlike the AruCo marker method, which allows for direct measurement of displacements.

Operators were divided in three groups, according to sizes C5, C50, C95, and each group consisted of ten people. Movement of the operators' upper limbs during the feeding of the chipper channel was controlled, considering their work confrontation zones.

The data processing algorithm applied to determine the areas of operators' hand movements consisted of five steps (Fig. 4). In the first step (Fig. 4a), the image recorded with the camera was converted into a

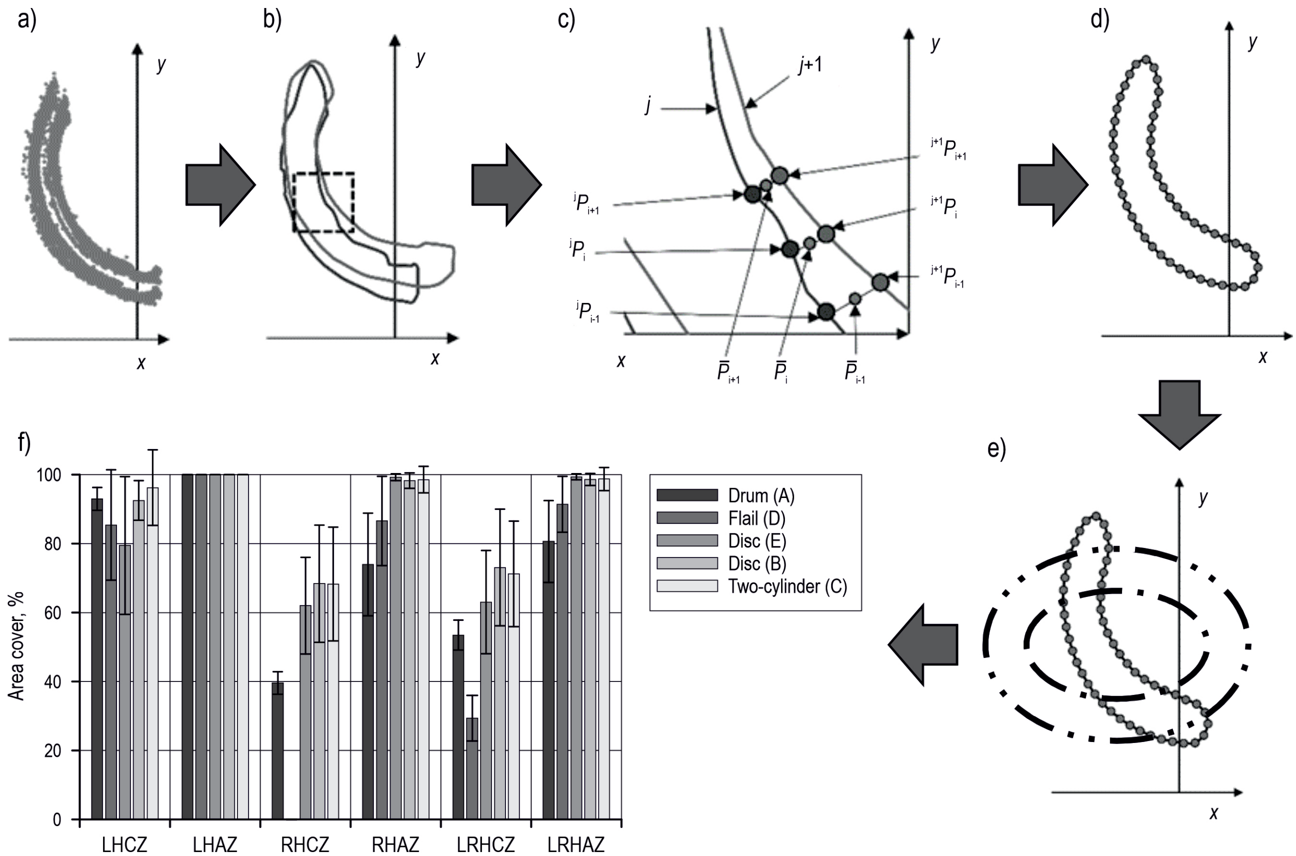

Fig. 4 Schematic representation of the motion capture data processing algorithm, where *x* – horizontal axis, *y* – vertical axis, *P* – point located on the loop describing the point cloud area, *j* – index numbering the analyzed loops, *i* – index for numbering the points on the loop, $\bar{P}$ – point on the averaged loop describing the hand reach, (a) point cloud generated from video image processing, (b) area describing the point cloud, (c) averaging the areas describing the designated areas, (d) generating an averaged area described by a set of 100 points, (e) comparing the limb movement areas with the comfort zones, (f) determining the percentage of the limb movement area in the comfort zones, LHCZ – percentage area of left hand movement in the comfort zone, LHAZ – percentage area of left hand movement in the allowed zone, RHCZ – percentage area of right hand movement in the comfort zone, RHAZ – percentage area of right hand movement in the allowed zone, LRHCZ – percentage area of left and right hand movement in the comfort zone, LRHAZ – percentage area of left and right hand movement in the allowed zone

set of points described by two coordinates, horizontal (*x*) and vertical (*y*). For this purpose, a proprietary software based on the OpenCV library was used (Wieczorek et al. 2020), which recognized the position of mobile sensors relative to marker *ID0*. Then, using the alpha shape algorithm (Liang et al. 1998, Giesen et al. 2006), the cloud acquired was described with a closed-loop (Fig. 4b). Using the algorithm, the alpha coefficient ranged from 0.7 to 0.9 depending on the point cloud density. After these steps, each loop was described by 100 $^{j}P_{i}$ points, where *j* is the index of the considered loop and *i* is the index of the currently considered point on the loop (Fig. 4c). Rhinoceros software with the Grasshopper module was used for this part of the study. The next step was to search for points where the distance between them was the smallest on all the determined loops. The mean point $\bar{P}_{i}$ was calculated from the points found using this method, which defined the average outline of the analyzed area (Fig. 4d). In the next step, limb movement and comfort and allowed zones were plotted (Fig. 4e). The final step was to calculate what percentage of hand movement while operating the chipper coincided with the defined ergonomic ranges (Fig. 4f).

Data distribution was checked against normality and a statistical analysis was performed to determine the confidence intervals for the mean, calculated on the basis of ten repetitions. When determining the confidence intervals, the Student's *t*-distribution and the 95% probability level (p=0.05) were used.

As part of the research, the impact on the limb (left or right) combined with the corresponding area of movement, and the type of chipper were assessed considering their coexistence as percentage of the

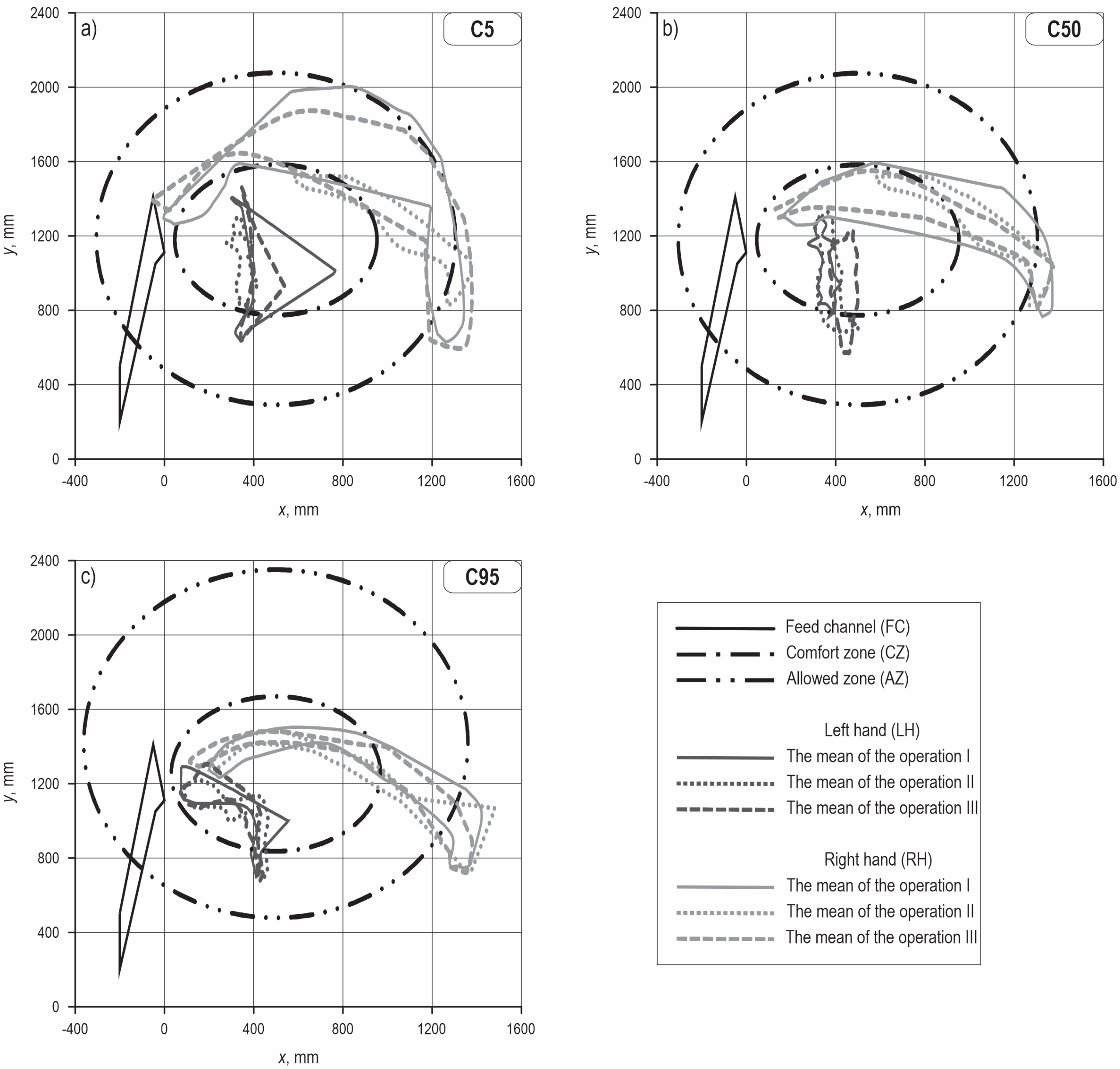

Fig. 5 Movement of upper limbs of operators with different anthropometric dimensions when feeding a drum wood chipper (A), where: (a) C5, (b) C50 and (c) C95

defined ergonomic ranges. For this purpose, statistical analysis was performed at the significance level set at α=0.05. Next, a two-parameter analysis of variance (ANOVA) was used to determine the effect of both variables in the experiment on the dependent one. A Tukey's HSD post-hoc test was applied when a significant difference was detected in the between-subject factor.

In the measurement error analysis, the arithmetic mean was taken as the estimator of the desired value, and the standard deviation of the arithmetic mean was taken as the error of the estimator.

3. Results

The results of the study describe the upper limb movements of woodchipper operators. These values are shown in the frontal plane, vertical (y) and horizontal (x) axis. Additionally, in the graphs showing upper limb movement (Fig. 5 and 6), feed channel (FC), comfort zone (CZ), and allowed zone (AZ) are labelled to facilitate the interpretation of the results. The graphs in Fig. 5 show mean motion of the left and right limb of operators characterized by different size: C5, C50 and C95. When the chipper mounts a drum

(A) cutting system, it can be noticed that the right limb moves in a larger area than the left limb. For the other chipper models (B, C, D, E), the movement of the upper limbs during feeding is illustrated only for size C95 (Fig. 6). It can be observed that depending on the type of cutting system and its corresponding FCs, the movement of the upper limbs varies. For the sake of clarity, only the mean movements for the first three out of ten operators are presented in Figs. 5 and 6.

To facilitate the analysis of upper limb movement in terms of possible musculoskeletal overload, the values of the surface covered by the upper limb movement

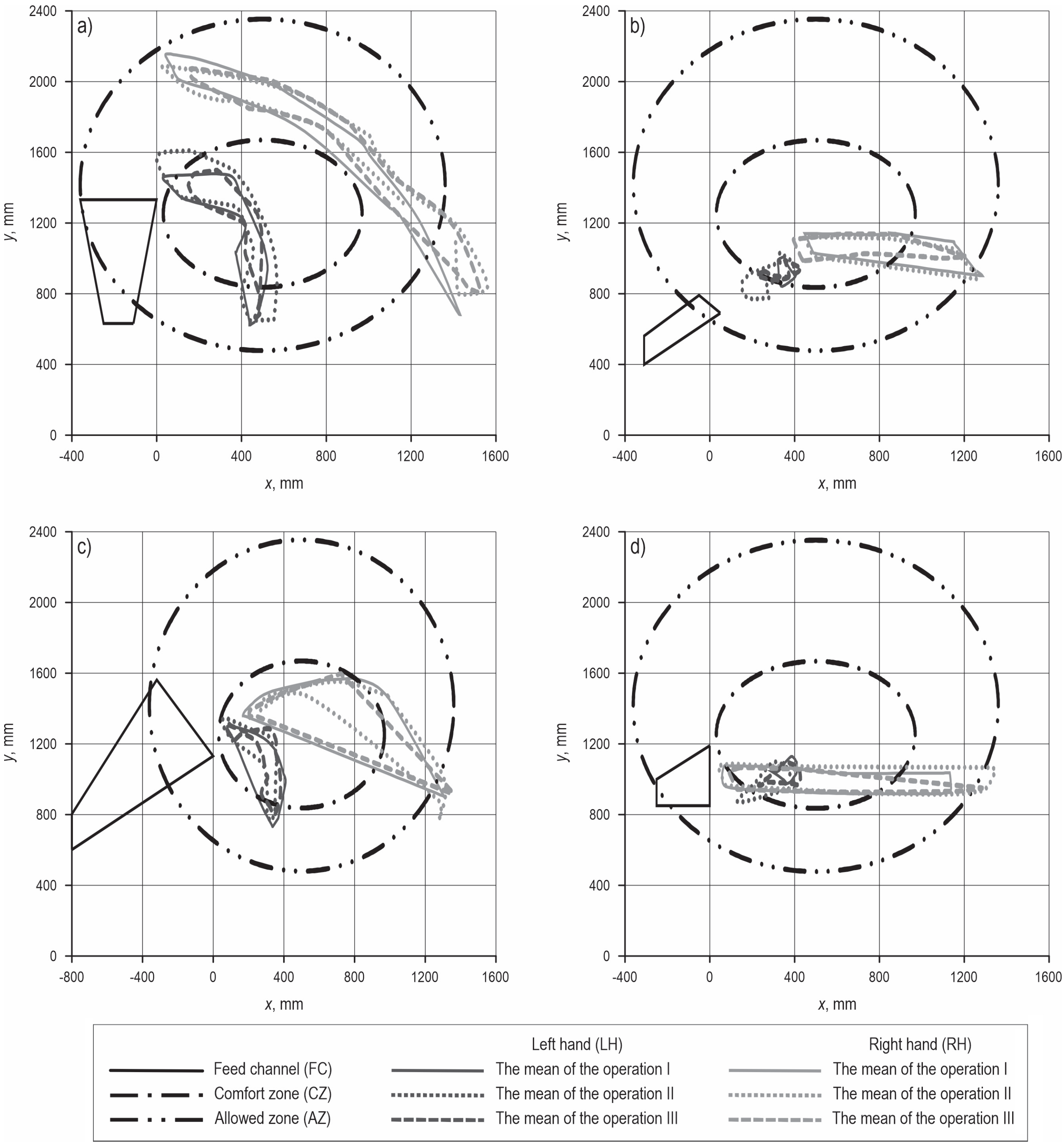

Fig. 6 Movement of the upper limbs of operators with anthropometric dimensions of group C95 when feeding a woodchipper with different cutting systems: (a) flail (D), (b) disc (E), (c) disc (B), (d) two-cylinder (C)

were related to CZ and AZ work areas. These values, related to a specific feed channel (Fig. 7) and to a defined human size (Fig. 8 and 9), are expressed as a percentage. Comparison of upper limb movement, resulting from the selected feed channel based on averaged limb movement values for all operators under test (Fig. 7), allows to evaluate the impact of these machines on average operators. It can be observed that the left hand, located closer to the feed channel, has more favorable working conditions than the right hand. The left hand is virtually always in the AZ, while 79% to 96% of limb movement during wood feeding to the machine is in the CZ. In terms of movement of the left limb, the most favorable characteristics are presented by the two-cylinder woodchipper (C) cutting system – 96%, while the least recommended, in terms of load on the musculoskeletal system, is the machine with two cutting systems, and the least advantageous characteristic is the E option (79%). Looking at Fig. 7b, this channel is too low. The right limb, further away from the FC, has a greater range of motion outside the CZ and the AZ working zones. The range of motion for the limb in the AZ is from 74% to 99%, while in the CZ – from 0% to 69%. With respect to musculoskeletal overload, the disc woodchipper E (AZ 99%, CZ 62%), B (AZ 98%, CZ 68%) and two-cylinder woodchipper C (AZ 97%, CZ 67%) have the best configuration. Flail woodchipper D (AZ 85%, CZ 0%) and disc woodchipper A (AZ 75%, CZ 40%) have the least successful ergonomic design. It can be noted (Fig. 7a) that feeding the flail woodchipper D machine is beyond the CZ range because the operator has to move high above his head. Determining the mean movement of the left and right hand, it can be seen that it is in the range of 80% to 98% in the AZ and 29% to 73% in the CZ. When analyzing the mean upper limb movement in the CZ, the most comfortable machine is the one with the disc woodchipper (B) (73%), while the least comfortable is the one with the flail wood chipper (D) (29%). On the other hand, in terms of work in the AZ, the disc wood chipper E, B, and two-cylinder wood chipper C have similar results of 98%, 97%, and 97%, respectively, while the drum wood chipper A and flail wood chipper D have the least promising results, with the value of limb movement contribution in the AZ equal to 80% and 92%, respectively.

Depending on the height of the operator (C5, C50, C95) and the woodchipper FC geometry, differences in the upper limb movement of the machine operator can be observed (Fig. 8 and 9). The upper limb movement of operators in different anthropometric dimensions is characterized by different proportion in the

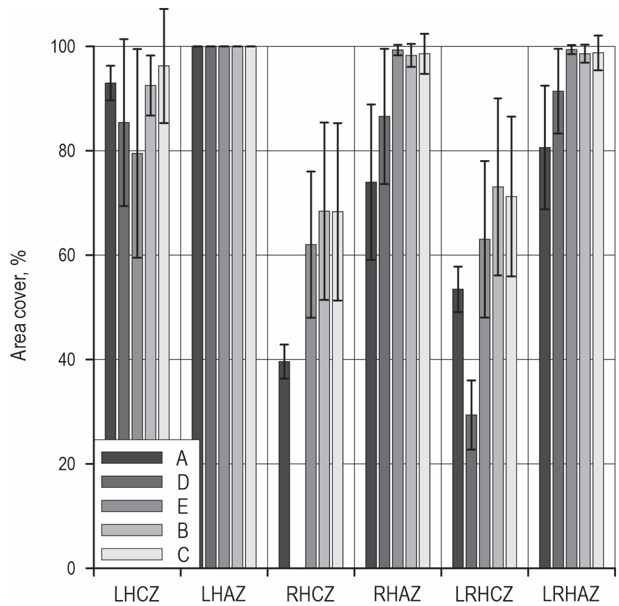

Fig. 7 Upper limb movement resulting from the applied cutting system based on the averaged values of limb movement of all operators considering the percentage of movement in the CZ and AZ zone, where: LHCZ – percentage area of left hand movement in the comfort zone, LHAZ – percentage area of left hand movement in the allowed zone, RHCZ – percentage area of right hand movement in the comfort zone, RHAZ – percentage area of right hand movement in the allowed zone, LRHCZ – percentage area of left and right hand movement in the comfort zone, LRHAZ – percentage area of left and right hand movement in the allowed zone; wood chipper: A – drum, B – disc, C – two-cylinder, D – flail, E – disc

AZ and CZ. It is clearly noticeable that the work of operators in the size group C95 is advantageous with machine B, shorter machine operators face worse working conditions, and their musculoskeletal system can be subjected to greater overloads. In other cases, the correlations are not as uniquely significant. From testing the disc woodchipper E machine, it can be seen that it mostly works well for operators in the C5 size group but increases the difficulty of use for taller operators. Differences in CZ performance depend on operator size and can be up to 51%, e.g., left limb movement in the CZ for an operator in the C5 size group is equal to 45% and in the C95 size group to 96% (Fig. 8).

It should be noted that commercial woodchippers used in urban areas typically induce overloads in the musculoskeletal system of the operator during their use. Working outside the AZ and CZ is characteristic of all machines and operators with different anthropometric dimensions (C5, C50, C95). No correlation has been seen between the operator size and the

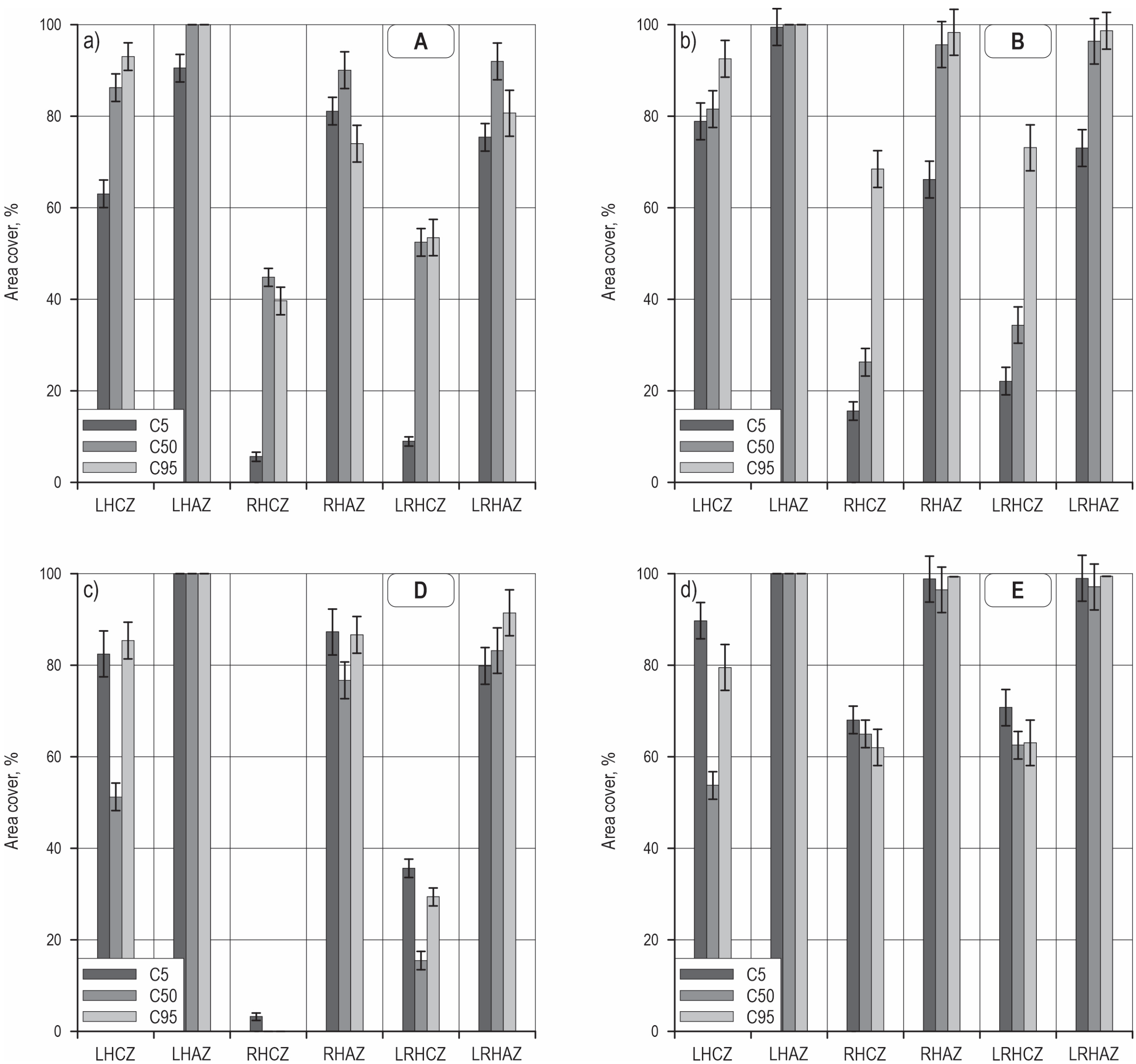

Fig. 8 Upper limb movement resulting from the applied cutting system based on the averaged values of limb movement of all studied operators considering the percentage of movement in the CZ and AZ zones, where: (a) drum, (b) disc, (c) flail, (d) disc, LHCZ – percentage area of left hand movement in the comfort zone, LHAZ – percentage area of left hand movement in the allowed zone, RHCZ – percentage area of right hand movement in the comfort zone, RHAZ – percentage area of right hand movement in the allowed zone, LRHCZ – percentage area of left and right hand movement in the comfort zone, LRHAZ – percentage area of left and right hand movement in the allowed zone

worsening of operator conditions, except in the two-cylinder woodchipper (B). In this case, larger operator size improved the working conditions. Based on the study, the authors see the need to develop adjustable FC in these machines, which could improve the ergonomics of the operation.

The ANOVA test (Table 3) shows differences for both arms and corresponding comfort and acceptable zones as well as the types of woodchipper (p_{val}<0.05). Interestingly, interaction of both variables for C5 centile turned out to be insignificant, however the p_val was very close to set significance level (p_{val}=0.05079). This allows to conclude that defined comfort and acceptable zones for both limbs, as well as the type of woodchipper and their combination, affect the averaged values of limb movement of all operators.

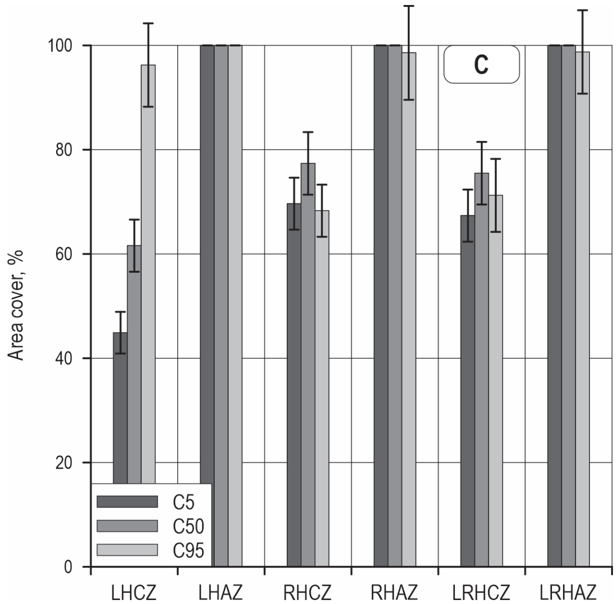

Fig. 9 Upper limb movement resulting from the use of a two-cylinder wood chipper (C) cutting system based on the values of upper limb movement of operators of different sizes C5, C50, C95 considering the percentage of movement in the zone, where: LHCZ – percentage area of left hand movement in the comfort zone, LHAZ – percentage area of left hand movement in the allowed zone, RHCZ – percentage area of right hand movement in the comfort zone, RHAZ – percentage area of right hand movement in the allowed zone, LRHCZ – percentage area of left and right hand movement in the comfort zone, LRHAZ – percentage area of left and right hand movement in the allowed zone

lead to injuries, inflammation, pain, and functional disorders. In forestry work, a health problem due to musculoskeletal disorders is back pain, and injuries to the upper and lower limbs. They are often the result of postural loading of machine operators engaged in tree care, logging, or wood processing processes. A large group of studies in this area concerns chainsaw operators showing an unacceptable level of physical load during cutting, debarking trees (Leszczyński and Pyzia 2012, Gallo and Mazzetto 2013, Dimou et al. 2022), or starting a chainsaw (Landekić et al. 2023). Masci et al. in 2022 showed that the trunk posture during debarking and cutting significantly affects the risk of biomechanical overloads among loggers (Masci et al. 2022). In 2023, Staněk et al. showed that the most burdened part of the operator's body at the end of the chainsaw operator's shift is the lumbar region (Staněk et al. 2023). The second most burdened parts of the body were the wrists and hands. The neck, on the other hand, was the least burdened part of the operator's body (Staněk et al. 2023). As shown by Arman et al. in Iran in 2022, musculoskeletal diseases are one of the most important occupational health problems in forestry occupations (Arman et al. 2022). Over eight out of ten patients reported at least one musculoskeletal overload symptom in the past 12 months, with the most commonly affected areas being the lower back (72.5%), feet and ankles (49%), and neck (41.2%) (Arman et al. 2022). Similar observations were made by Schettino et al. in 2021 in Brazil, where the analysis

Table 3 Statistical data of analysis of variance (ANOVA); c – *F* test value, p_{val} – test probability of ANOVA

Centile	C5		C50		C95	
Statistical value	*F*	p_{val}	*F*	p_{val}	*F*	p_{val}
Type of wood chipper	8.02552653	$2.99 \cdot 10^{-5}$	24.6539	$4.24 \cdot 10^{-12}$	29.31348	$1.61 \cdot 10^{-13}$
Movement of limbs in zones	21.8823278	$2.1 \cdot 10^{-12}$	89.09698	$1.87 \cdot 10^{-26}$	108.594	$9.73 \cdot 10^{-29}$
Interaction	1.74580919	0.050379	5.969074	$3.41 \cdot 10^{-8}$	7.835778	$2.38 \cdot 10^{-10}$

4. Discussion

Overloading of the musculoskeletal system of the upper limbs can be harmful if not managed properly. The time after which overloading can become harmful may vary depending on many factors such as the intensity and type of physical activity, individual health conditions, age, and lifestyle. When it comes to the time when overloading can start to be harmful, there is no straightforward answer because it depends on individual factors. However, chronic improper loading of the muscles and joints of the upper limbs can of cutting, debarking, manual extraction, and manual loading of wood activities showed a very high risk of repetitive musculoskeletal overload injuries exceeding permissible loads (Schettino et al. 2021). The difficult working conditions in the forestry sector also contribute to the occurrence of musculoskeletal disorders among workers, as signaled by Dimou et al. in 2020 during the analysis in Greece (Dimou et al. 2020). Among workers whose main task was debarking and stacking firewood, musculoskeletal overload symptoms affected areas such as wrists and hands (65%), knees (57%), and lower back (52%). A high percentage

(41%) of participants also reported symptoms in their shoulders and upper back (Dimou et al. 2020). In Brazil, studies were also conducted on the impact of manual forest planting on human body discomfort, showing that manual planting caused greater discomfort in the legs of 56% of workers, while fertilizing and herbicide use caused discomfort in the arms of 41% and 56% of workers, respectively (Lopes et al. 2018).

The Authors found only one study available in the literature regarding musculoskeletal overload, it involved a study of a woodchipper with a horizontal FC (similar to the C design in this study), which also showed that working on this machine causes musculoskeletal overload (Cremasco et al. 2019). The problem of overloading the musculoskeletal system is also recognized among operators of loaders for wood chipping machines (Martins et al. 2020). The possibility of changing the musculoskeletal overload by changing the operator size in manually fed machines, is also recognized in agricultural (Abd Rahman et al. 2015, Kong et al. 2018), forestry (Gerasimov and Sokolov 2014), in sawmills (Qutubuddin et al. 2013) and small scale industries (Ansari and Sheikh 2014, Ishak et al. 2021), manufacturing and processing (Yadi et al. 2018, Tiogana and Hartono 2020, Arendra et al. 2020) works. Borz et al. in 2019 demonstrates that manual biomass harvesting from coppices in Romania may expose brush cutter operators and assistants to, among other things, uncomfortable postures during work (Borz et al. 2019). The Postural Risk Index was evaluated at 191.11% for the worker handling the brush cutter and at 192.02% for the manual assistant, indicating rather reduced risks, but also the need to evaluate how the dynamic work of the upper limbs would affect the workers' health (Borz et al. 2019).

There are scientific studies and diagnostic tools that allow for the assessment of musculoskeletal overloads in relation to occupational activity and the risk of musculoskeletal disorders. Ergonomic studies may involve analyzing body posture, movements, and loads during occupational tasks, using observations as well as advanced measurement technologies such as load sensors, cameras, or electromyography. These methods can help identify areas where potential overloads and physical stress on the musculoskeletal system occur. Additionally, there are epidemiological studies that analyze the relationship between types of work, duration of work, and the occurrence of musculoskeletal disorders. These studies can provide important information about risk factors and help identify occupational groups at higher risk of injuries and work-related disorders. In clinical practice, the assessment of the risk of musculoskeletal disorders often includes a patient interview regarding their occupational history and current symptoms, allowing physicians and rehabilitation specialists to personalize the risk assessment and appropriately plan therapy and prevention strategies.

Because all actions improving the quality of work for machine operators are important, research by Lachowski et al. in 2017 highlights the significance of the relationship between job satisfaction and the occurrence of musculoskeletal disorders (Lachowski et al. 2017). According to Lachowski, shaping working conditions that are a source of job satisfaction should be considered one of the main elements of musculoskeletal disorder prevention. Considering the nature of work in forestry, actions should be taken such as implementing professional training and promoting the use of protective measures, as well as the development of machines and work methods optimized for ergonomics, such as ensuring correct posture when starting a chainsaw (Landekić et al. 2023), and tools to assist with manual wood loading (Schettino et al. 2017).

Among the developments in wood chippers operated manually, an adjustable feed channel height is expected to be implemented based on the anthropometric size of the operator. The current analysis of the state of the technology shows that machines available on the Central European market do not consider designing a comfortable operator position during the design process. The presented areas of limb movement recommended based on anthropometric research and the ranges and areas of limb movements of operators examined in this article allow for better design of feed channel wood chippers.

Similar proposals for comfort zones (CZ) and acceptable work zones (AZ) were presented in the article by Wieczorek et al. in 2023 for wheelchair operation (Wieczorek et al. 2023). In this work, zones were defined based on the length of the kinematic chain moving a marker attached to the hand. Comfort in this article was defined by the length of the kinematic chain, e.g., the most comfortable zone resulted from the movement before the shoulder and the lack of movement of the arm (Wieczorek et al. 2023). Applied to the design of feed channel wood chippers, the whole kinematic chain must considered, from the foot to the hand. The zones investigated in the article focuse the differences in muscle effort; when moving within the CZ zone, the operator's hands were closest to the torso, resulting in a shorter lever arm of the branch's gravitational force inserted into the feed channel. This resulted in less strain on the musculoskeletal system with a lower value of the gravitational force moment compared to the AZ zone. Therefore, when designing the feed channel, it should be positioned at a height and distance from the operator so that the feeding process only requires hand movement within the area defined by the CZ zone. This is difficult to achieve in practice, so efforts should be made to minimize the time spent moving outside the CZ zone.

In the future, these works may address the perceived shortage of forestry workers, as observed, for example, in Bosnia and Herzegovina (Šporčić et al. 2023), and fall within the framework of the eight core variables (equipment and training) that influence job satisfaction in forestry in Indonesia (Yovi and Yamada 2019).

A limitation of the article is the analysis focusing only on male operators with characteristic sizes for men from Central Europe. The movement study area included the position from holding the wood at hip level, to feeding it to the FC – the operator in this position kept the lower limbs on the ground. The main movement was in the frontal plane, so only this movement was subject to analysis.

5. Conclusions

The problem of overloading the musculoskeletal system during the use of machines employed for comminution, where wood is manually fed by operators, is still present. Studies of woodchippers commonly used in urban areas with different cutting systems (drum, disc, two-cylinder, flail) characterized by different FC geometries have shown overloading of upper limbs. Mean upper limb movement can be contained in the AZ from 80% to 98% and in the CZ from 29% to 73%. The limb closer to the feed channel has more favorable working conditions in most cases, and between 79% and 96% of limb movement is in the CZ. In contrast, the limb working further away from the FC has limited movement in the AZ – from 74% to 99% and in the CZ – from 0% to 69%. The difference between limbs in their movement proportion in specific zones may exceed 51%. There are no perceived correlations showing that machines are manufactured for a selected operator height (C5, C50, C95), all studied operators were subjected to musculoskeletal overload. The paper provides information that the available manufactured machines are characterized by non-ergonomic FCs, regardless of their geometry, which varied significantly. Further research should be conducted in interdisciplinary teams: designers, machine operators, anthropologists, ergonomics experts, physicians, and mechatronic engineers should collaborate to develop adjustable FCs, to improve operators' comfort.

Appendix A

A complete list of all notations and physical quantities used in this paper can be found in Appendix A in Table A1.

Table A1 List of marking used in the paper

Symbol	Description
A	Drum wood chipper
ANOVA	Analysis of variance
AZ	Allowed zone
B	Disc wood chipper
C	Two-cylinder wood chipper
CZ	Comfort zone
C5	Bottom centile
C50	Median centile
C95	Top centile
D	Flail wood chipper
i	Index of the currently considered point on the loop
ID0	Marker
j	Index of the considered loop
E	Disc wood chipper
F	Test value
FC	Feed channel
LHAZ	Percentage area of left hand movement in the allowed zone
LHCZ	Percentage area of left hand movement in the comfort zone
LRHAZ	Percentage area of left and right hand movement in the allowed zone
LRHCZ	Percentage area of left and right hand movement in the comfort zone
P	Loop
$\overline{P}$	Mean point
p	Probability level
p_{val}	Test probability of ANOVA
REBA	Rapid entire body assessment
RHAZ	Percentage area of right hand movement in the allowed zone
RHCZ	Percentage area of right hand movement in the comfort zone
RULA	Rapid upper limb assessment
SI	Spark ignition
x	Horizontal coordinates
y	Vertical coordinates

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