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Ergonomic Testing for the Design of an Innovative Mail Delivery Vehicle: A Physical Mock-up Case Study

Morgane Roger[1], Nicolas Vignais[1,2,3]*, François Ranger[1,4] and Jean-Claude Sagot[1]

[1]ERCOS, Université de Technologie de Belfort-Montbéliard, Site de Montbéliard, 90010 Belfort Cedex, France
[2]CIAMS, Universite Paris-Sud, Université Paris-Saclay, 91405 Orsay Cedex, France
[3]CIAMS, Université d'Orléans, 45067, Orléans, France
[4]Université du Québec à Montréal, Montréal, Québec, Canada

Abstract

The aim of this study was to provide ergonomic recommendations concerning passenger compartment dimensions of an innovative vehicle dedicated to mail delivery. To this aim, an ergonomic analysis of egress/ingress postures has been performed on a physical mock-up, which is considered as a reliable tool when investigating driving space. Six workers with different anthropometries participated to the experiment. The influence of three seat heights, two headlining heights and three headlining widths were tested while participants performed a simulated mail delivery task. Based on goniometers and video observations, a Rapid Entire Body Assessment (REBA) was conducted. Perceived discomfort was estimated with a Category Partitioning Scale (CP-50). Results showed that REBA scores were mainly at medium risk (5.18 ± 1.75). Discomfort scores were significantly influenced by seat height ($\chi2$ (2) = 7.79, p = 0.02), especially for short participants when seat height was equal to 760 mm (Z = -2.21, p = 0.03). REBA scores and discomfort scores were significantly higher for the lowest headlining height and the highest headlining width. Outcomes of this study permitted to establish that: the seat height has to be adjustable (between 580 mm and 760 mm), the headlining height has to be fixed to 1360 mm, and the headlining width has to be comprised between 300 and 525 mm. The results from this research suggest that physical mock-up can provide a useful tool for defining suitable dimensions for the design of a future vehicle, taking into account anthropometric characteristics of the target population.

Keywords: Physical ergonomics; Physical mock-up; Vehicle design; Anthropometry

Introduction

The automotive industry is a lucrative but highly competitive industry with more than 50 major manufacturers worldwide [1]. Thus, automotive manufacturers must quickly propose new products that meet end-users' needs to retain their share of sales in a contracting market.

Understanding and integrating the customer's needs into a product, so called user-centered design, provides functionality into this product from which the user will derive benefits [2,3]. The principle of user-centered design states that "if an object, a system or an environment is intended for human use, then its design should be based upon the physical and mental characteristics of it human users" [4]. In the automotive context, this design process implies at some point, testing a prototype of the vehicle with various target users' anthropometric characteristics to integrate suitable dimensions to the final product [5,6]. As it may appear difficult to recruit such various participants directly in the field, International Standard ISO 15537 [5] also mentioned that digital human models (DHM) can be used through this step.

Integrating DHM into the industrial process has often been proposed as a strategy to design safer and efficient products while optimizing productivity and cost [7]. Indeed DHM supports the ergonomic evaluation of new vehicle design during early stages of the process, by modelling anthropometry, posture, motion or predicting discomfort (see e.g. [8]). Nevertheless, it is necessary to accurately posture the virtual manikin to effectively use DHM [9]. Some researchers have demonstrated that large errors can occur when these postures are compared to those adopted by workers performing the actual task in their genuine physical environment [10-12]. Moreover, manipulating the virtual manikin has been identified as a time-consuming method for obtaining postures in work simulation [13] as it significantly depends on the assessor's abilities [14].

In parallel to DHM, physical mock-ups will appear to be a reliable tool in vehicle product development, especially when understanding the driving space and the act of getting in/out of the cab [15-18]. Contemporary physical mock-ups can be fully adjusted to various vehicle interiors in order to evaluate usability and ergonomics before real products are manufactured. For example, Sang and colleagues [19] used a physical mock-up to test the impact of anthropometric characteristics of a target population on vehicle design. Through physical mock-up, researchers have been able to assess ergonomic aspects of the vehicle such as reachability, spatial perception and size estimation [20] and then turned it into industrial production. This tool enabled designers to adopt an applied user-centered design approach as participants testing the physical mock-up are real and not virtual manikins. Moreover, physical mock-ups are considered as a reliable ergonomic technique into the International Standard ISO 6385 [21]. This Standard establishes the fundamental principles of ergonomics as basic guidelines for the design of optimal work systems in a user-centered design approach. It also recommends "to design a work system for a broad range of the design population in order to meet

***Corresponding author:** Nicolas Vignais, CIAMS, Université Paris-Sud, Université Paris-Saclay, 91405 Orsay Cedex, France, Tel: +33 169154703; E-mail: nicolas.vignais@u-psud.fr

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the needs of workers with various characteristics, including people with special requirements, as far as possible" (p. 3). More specifically, a mock-up is the foundation of the work on which communication and collaboration are established between the various actors involved in the design process [22]. The present study then used a physical mock-up to define ergonomic requirements to design a special vehicle dedicated to mail delivery.

Most mail carriers use cars, bicycles or walk to deliver mail along their route. When walking, slip, trip and fall accidents may occur [23,24]. Moreover, mail carriers can deliver 2500 letters per day on average with a delivery period being 4 to 5 hours daily [25]. When bicycling, the physiological demand is greatly increased, especially with hilly geographical profile [26]. Moreover, when bicycling or walking, one of the main difficulties experienced by the operators is linked to the bag they use during their rounds. Through a functional and ergonomic study of load distribution with this kind of bag, Reinert and Lucio [25] showed that it is necessary to change the way of carrying mail during delivery activity. For all these reasons, it appears necessary to conceive new ways to deliver mail. To avoid risks linked to walking and bicycling when delivering mail, the design of an ergonomic vehicle dedicated to this activity can be a solution. This vehicle will have to meet different challenges: i) being compact and easy to handle, ii) providing enough space for carrying a large amount of letters and packages, iii) permitting to deliver mail quickly without getting out of the vehicle when possible, iv) presenting an ergonomic access to the headlining area to improve ingress and egress postures when having to go out and into the vehicle.

The design of this innovative vehicle was part of the objective of the European Project MobyPost (http://mobypost-project.eu/) coordinated by the University of Belfort Montbeliard (UTBM). This project aimed at equipping, in genuine conditions, two French experimentation sites, located in Franche-Comté (East of France), with special vehicles dedicated to mail delivery activity handled by the French Post Office (La Poste). Toward this ends, researchers from the project were asked to develop an ergonomic vehicle which could fit end-users needs and mail delivery activity's requirements. To meet the previously described challenges, researchers proposed to design a vehicle with: i) one space for the worker, ii) a spacious trunk, iii) an open-air cab, iv) an enlarged vehicle access area. This latter point was critical as it would permit to decrease the risk of musculoskeletal disorders despite the high frequency of ingress and egress motions.

Thus, the aim of the present study was to examine the influence of three critical dimensions of a vehicle dedicated to mail delivery activity, among which seat height (SH), headlining height (HH) and headlining width (HW), on motion and postures necessary to get out and in of the vehicle. A physical mock-up has been used to configure different sizes of these critical dimensions. To be consistent with the International Standard ISO 6385 [21], mail carriers with stature close to the 5th and the 95th percentiles were tested. Concerning access to the vehicle, an ergonomic and biomechanical assessment was conducted based on joint angles, REBA scores and global discomfort scores. It has to be noted that this case-study was supported mainly by the UTBM, Ducatia- Energia and La Poste. Thus, time and cost requirements had to be taken into account while employing the physical mock-up without negatively impacting the project constraints and pace.

Materials and Methods

Participants

Six right-handed healthy mail carrier volunteers, three women and three men, with no history of musculoskeletal disorders participated in the experiment (weight: 64.2 ± 12.4 kg; age: 43.8 ± 4.1 years; years of experience: 17.2 ± 6.8). These participants have been selected based on the Standard ISO 15537 procedure about preliminary design test [5]. When testing a free space dimension like HH and HW, this standard mentions that participants should own to the 95th percentile. Conversely, when assessing a reaching dimension like the distance between seat and wheel, participants should correspond to the 5th percentile. In the current study, although women were close to the 5th percentile in height, men were much like the 95th percentile according to the Belgium comparison population (Table 1) [27]. Thus, women and men have been respectively associated to anthropometric groups G5 and G95, starting from the hypothesis that women and men would react similarly to go in and out of the vehicle. The study protocol was approved by the academic ethics board and all participants provided informed written consent.

Materials

Multiscale physical mock-up for passenger compartment: A physical mock-up was used to simulate the future vehicle dedicated to mail delivery (Figure 1a). This mock-up was composed of a fully adjustable aluminum structure where passenger compartment elements, i.e. seat, wheel and gear lever, have been attached (Figure 1b). Elements of the aluminum structure may be adjusted for all degrees of freedom in translation.

Camcorders: Four camcorders were placed around the physical mock-up in order to film participants' egress/ingress movements during the experimentation.

Goniometers: Each participant was equipped with 4 goniometers (BIOMETRICS LTD., Gwent, UK) placed as follow:

- Knee: a uniaxial goniometer was placed on each knee to record flexion/extension movements of the shank relative to the thigh (Figure 2a).
- Lower back: a bi-axial goniometer was placed on the lower back to record flexion/extension and right/left lateral flexion movements of the trunk relative to the pelvis (Figure 2b).
- Neck: a bi-axial goniometer was placed on the neck to record flexion/extension and right/left lateral flexion movements of the head relative to the trunk (Figure 2c).

Biometrics Data Log system (BIOMETRICS LTD, Gwent, UK) was used for signal conditioning coming from the wired goniometers during the experiment. The signal was stored at 1000 Hz. Joint angles were then resampled at 25 Hz using a moving-average process through the CAPTIV software (TEA ERGO, Nancy, France).

Group	Subject	Weight (kg)	Height (mm)	Height of the comparison population (mm)	
G5	S1	53	1610		
	S2	51	1600		
	S3	55	1530		
	Mean	*53 ± 2*	*1580 ± 43.6*	*5th percentile*	*1551*
G95	S4	75	1870		
	S5	73	1910		
	S6	78	1820		
	Mean	*75.3 ± 2.5*	*1866.7 ± 45.1*	*95th percentile*	*1861*

Table 1: Weight and height values for each subject, group and the comparison population [27].

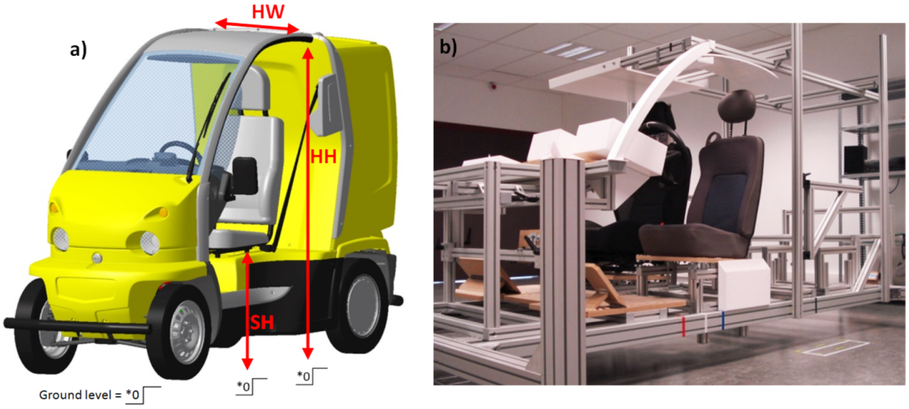

Figure 1: The future MobyPost vehicle in CAD model (a), and the multiscale physical mock-up with passenger compartment elements (b).

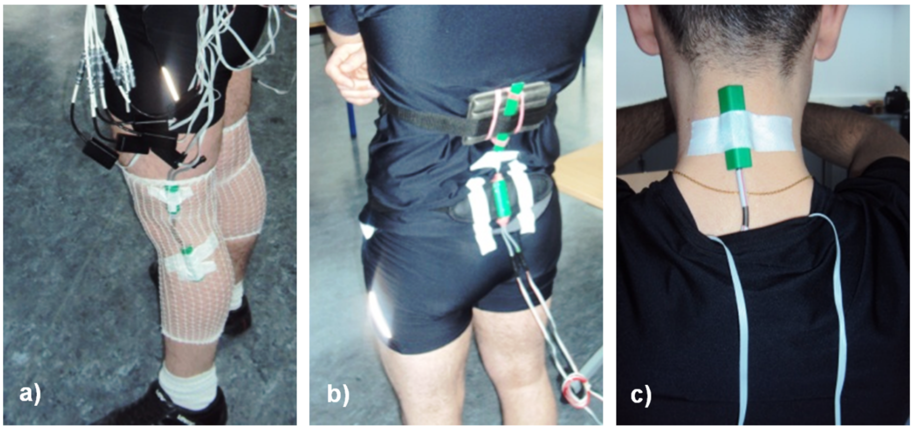

Figure 2: Placement of the goniometers on the knee (a), the lower back (b) and the neck (c).

Procedure

Preparation: Before the experiment, each participant signed an informed consent, anthropometric dimensions were measured (height and weight), and age and years of experience were gathered. She/He was then equipped with the four goniometers and professional clothing including jacket, pants and gloves. The participant was asked to perform the task at a normal pace and as naturally as possible. Prior to the experiment, each participant had a training period of 10 minutes to get used to the camcorders, goniometers and the physical mock-up. During this period, each participant was asked to repeat the task as many times as she/he liked. Each participant also had to adjust the position of the seat longitudinally to the most comfortable position.

Task: During the experiment, the participant had to perform egress/ingress movements like in a mailing delivery activity: she/he first had to find a specific mail in a mail batch when seated into the physical mock-up; then she/he was asked to exit vehicle mock-up and put the mail into one of the two mail boxes installed on both sides of the mock-up; finally the participant had to enter the vehicle and sit. Between each egress/ingress movement, the participant had to complete discomfort questionnaires (see below).

Experiments: In the current study, three SH (SH1, SH2, SH3), two HH (HH1, HH2) and three HW (HW1, HW2, HW3) have been tested (Table 2). Insofar as SH is a key measure from which other elements are designed in a car (e.g., wheel, brake's and accelerator's pedals, etc.), it was investigated with fixed values of HH and HW. Then these two latter factors have been examined in interaction.

Car dimension		Value (mm)
Seat height	SH1	580
	SH2	670
	SH3	760
Headlining height vs. Headlining width	HH1 × HW1	1260 × 300
	HH1 × HW2	1260 × 525
	HH1 × HW3	1260 × 750
	HH2 × HW1	1360 × 300
	HH2 × HW2	1360 × 525
	HH2 × HW3	1360 × 750

Table 2: Values of the tested critical dimensions.

Thus, the experiment was composed of two parts: influence of SH (i), and influence of HH and HW (ii).

i) During this part of the experiment, each participant had to perform three repetitions of egress/ingress movement per SH (SH1, SH2 and SH3) in a randomized order. In total, 9 movements were recorded for each participant. It has to be noted that HH2 and HW2 values have been used during this part of the experiment.

ii) This part was used to test the interactive influence of the HH and HW. Thus each participant had to perform three repetitions of egress/ingress movement per condition. As all HW conditions (HW1, HW2, HW3) have been tested for each HH condition (HH1, HH2), 18 movements were recorded for each participant in total. It has to be noted that SH2 value has been used during this part of the experiment.

These two parts and underlying conditions were presented to the participant in a randomized order. A break of 5 minutes was given to the participant between the two parts of the experiment.

Ergonomic assessment

Joint angle analysis: Joint angles obtained from electrogoniometers (lower back, neck and knees) were examined continuously during the egress/ingress movements.

REBA score: The REBA is an ergonomic tool that estimates the risks of work-related entire body (right and left sides) disorders, as low back injuries, by computing a global risk score [28]. The REBA method stipulates a negligible risk, a low risk, a medium risk, a high risk, and a very high risk with a score between 1 and 2, 2 and 4, 4 and 8, 8 and 11, and beyond 11, respectively. This score is based on body posture, forceful exertions, type of movement or action, repetition, and coupling. Concerning body posture, the REBA assessment method is based on particular joint angles: neck, trunk relative to the pelvis, knees, shoulders, elbows and wrists. Although goniometers previously described provided four angles of the REBA table, other joint angles have been deduced from video film analysis. More precisely, the ergonomist had to stop the videos at the different key postures (see below) and change to a view (on the four camcorders) which was more in the plane of the movement to deduce joint amplitude. As the REBA method has been designed for discrete observations of the body, each movement was split up into six postures, i.e. 3 egress and 3 ingress postures (Figure 3) [29,30]:

– Egress:

P1. The left foot leaves the vehicle floor

P2. The left foot passes above the still

P3. The left foot reaches the ground

– Ingress:

P4. The right foot passes above the still

P5. The right foot touches the vehicle floor

P6. The participant is in driving position

Perceived discomfort: The subjective evaluation of discomfort has been collected orally at the end of each ingress and each egress motion. To this aim, a Category Partitioning Scale (CP-50) was arranged vertically from 0, equal to “no discomfort”, to 50, equal to “highest discomfort” [31]. There were five discomfort categories: very slight, slight, medium, severe and very severe. Each category was divided into 10 scale points. This scale was chosen because of its well-known validity and reliability to measure comfort in seated posture [31].

Data analysis

In this study, dependent variables were the REBA scores and the perceived discomfort scores. The independent variables corresponded to the SH (SH1, SH2, SH3), the HH (HH1, HH2), the HW (WH1, WH2, WH3) and the anthropometric factor (G5 and G95). The posture (3 ingress postures and 3 egress postures) was also considered as an independent variable but only when analyzed in association with REBA scores. For each participant, an average value was computed for each dependent variable based on the three repetitions of ingress and egress movements. Based on Zhu [32], there were three null hypotheses:

- no dependent variable differences between SH1, SH2 and SH3 conditions.
- no dependent variable differences between HH1 and HH2 conditions.
- no dependent variable differences between HW1, HW2 and HW3 conditions.
- And consequently, three alternative hypotheses:

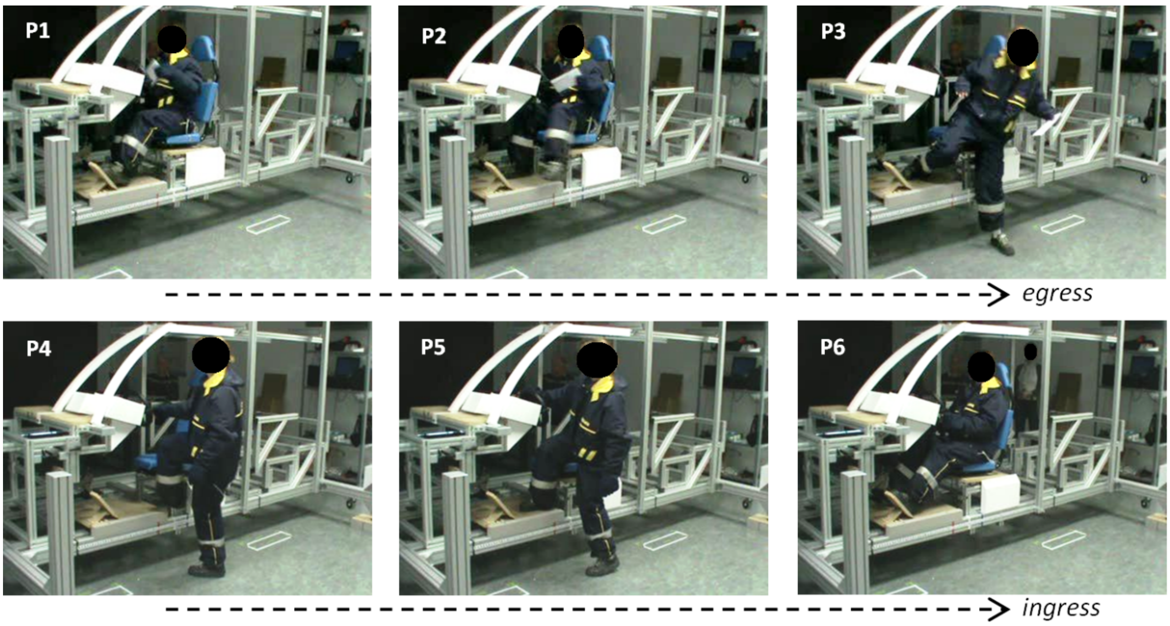

Figure 3: The six key postures analyzed during egress (P1, P2, P3) and ingress (P4, P5, P6) movements.

- at least two of the conditions were significantly different from each other between SH1, SH2 and SH3 conditions.
- the HH1 condition was significantly different from HH2 condition.
- at least two of the conditions were significantly different from each other between HW1, HW2 and HW3 conditions.

We used a Type I error of 0.05 for all statistical tests. Given our small sample size, a non-parametric statistical analysis has been performed using the Friedman test which is the non-parametric alternative to the one-way ANOVA with repeated measures. As the SH was analyzed independently from the HH and HW, a series of 3 (SH) x 2 (anthropometric groups) and a series of 2 (HH) x 3 (HW) x 2 (anthropometric groups) randomized block analysis of variance (Friedman's test) were used to assess REBA scores and discomfort results. Probability values below 0.05, 0.01 and 0.001 were, respectively, considered significant, highly significant and very highly significant in this study. Significant effects were further investigated using Wilcoxon signed-rank tests with a Bonferroni correction applied.

Results and Discussion

The objective of this study was to perform an ergonomic analysis to recommend specific dimensions for the design of a vehicle dedicated to mail delivery. Thus main results of joint angles, REBA scores and discomfort scores are presented and discussed according to dimension parameters (SH, HH, HW), egress/ingress postures (P1 to P6), and anthropometry. The dimensions of the future vehicle were simulated by using a fully adjustable physical mock-up.

Joint angles were analyzed in terms of differences between G5 and G95 groups (Figure 4), as they were no significant difference between joint angles across SH conditions, and HH and HW conditions.

Joint angles analysis revealed that there was more range of motion for lateral flexion angle of the neck for the G95 group during both egress and ingress motion, although amplitude appeared quite low. The range of motion of flexion/extension angle of the neck was more pronounced for the G95 group during the egress movement (from +20° to -20°). Back lateral flexion angle did not present a high range of motion during egress and ingress motion for both groups. G5 group did a greater extension and a greater flexion of the back during egress and ingress movements, respectively. Flexion/extension angles of right and left knees showed similar trends across egress/ingress motion, except for the left knee which appeared more flexed at the end of the ingress movement. This was probably due to the fact that participants of the G5 group placed their left foot flat to the ground before adopting a more extended posture in the driving position.

From a general point of view, REBA scores computed during both parts of the experiment were at medium risk, i.e. "further investigations are necessary and changes have to be applied soon" [28] (Table 3). Despite the small number of participants, the influence of anthropometry on the ergonomic assessment has been examined in order to express specific needs of G5 and/or G95 populations in terms of vehicle dimensions (Table 3). Mean REBA scores of G5 group were always lower than mean REBA scores for G95 group, except for SH3 condition.

Discomfort scores, recorded after each movement of ingress or egress, were obtained for each dimension condition (SH, HH, HW). Discomfort scores are further discussed in light of vehicle dimensions and anthropometry (Table 4).

Influence of SH

Discomfort scores increased significantly with the height of the seat after running a Friedman test ($\chi 2(2) = 7.79$, $p < 0.05$). Post hoc analysis revealed that there was a statistically significant increase in perceived discomfort between SH2 and SH3 conditions ($Z = -2.19$, $p < 0.017$ due to Bonferroni corrections). Concerning the influence of anthropometry and SH on discomfort scores, G5 group perceived a significant higher discomfort comparing to G95 group in SH3, i.e. when the seat was at its highest position ($Z = -2.21$, $p < 0.05$).

However, it has to be noted that effect size standard belongs to "large" (≥ 0.8 = large; <0.8 to >0.2 = medium; ≤ 0.2 = small) for some discomfort score comparisons (Table 5) [33]. Thus the small sample size may explain why the null hypothesis was not rejected for those comparisons. In those cases, the recommended sample size per group needed to get enough power has been computed [32] (Table 5).

As REBA scores have not been influenced by SH, posture and anthropometry, the three SHs appeared objectively adapted to the population of mail carriers. This was confirmed by the joint angle analysis as continuous goniometric data obtained for the three SH did not present any significant difference during egress and ingress motion. Conversely, the subjective assessment, i.e. the discomfort score, significantly increased at SH3 compared to the discomfort score obtained at SH2 (Table 4), but this result was mostly due to the

Vehicle dimension		REBA scores ± SD		
		G5	G95	Mean
Seat height	SH1	4.63 ± 1.21	5.04 ± 1.81	4.8 ± 0.73
	SH2	4.91 ± 1.42	5.17 ± 1.56	5 ± 0.73
	SH3	5.08 ± 1.65	4.92 ± 1.47	5.04 ± 0.79
Headlining height	HH1	5.45 ± 2.67	5.72 ± 2.46*	5.59 ± 2.57$^{\mu}$
	HH2	4.81 ± 1.86	5.28 ± 2.44*	5.05 ± 2.14
Headlining width	HW1	5.08 ± 2	5.16 ± 2.17	5.12 ± 2.02
	HW2	5.08 ± 2.4	5.17 ± 2.39	5.13 ± 2.38
	HW3	5.23 ± 2.56	6.17 ± 2.69***	5.7 ± 2.66¤

$^{\mu}$REBA scores significantly different (between HH1 and HH2, $p < 0.05$).
¤REBA scores significantly different (HW3 vs. HW2, and HW3 vs. HW1, $p < 0.017$ due to Bonferroni adjustments).
*REBA scores significantly different between G5 and G95 ($p < 0.05$).
***REBA scores significantly different between G5 and G95 ($p < 0.001$).

Table 3: Ergonomic assessment according to vehicle dimensions and anthropometry.

Vehicle dimension		Discomfort scores ± SD		
		G5	G95	Mean
Seat height	SH1	7.17 ± 11.41	8.06 ± 7.06	7.6 ± 9.06
	SH2	9.28 ± 9.39	10.5 ± 11.6	9.9 ± 10.08
	SH3	37.61 ± 14.29*	10.94 ± 11.07	24.28 ± 18.51$^{\mu}$
Headlining height	HH1	8.3 ± 8.66	17.59 ± 12.07**	12.94 ± 11.38
	HH2	9.28 ± 9.39	10.5 ± 11.6	9.82 ± 9.68
Headlining width	HW1	3.42 ± 4.86	13.81 ± 9.14**	8.6 ± 8.91
	HW2	9.14 ± 7.01	10.25 ± 9.58	9.69 ± 8.23
	HW3	9.28 ± 9.67	22.42 ± 12.8**	15.85 ± 12.8¤

$^{\mu}$Discomfort scores significantly different (between SH2 and SH3, $p < 0.017$ due to Bonferroni adjustments).
¤Discomfort scores significantly different (HW3 vs. HW2, and HW3 vs. HW1, $p < 0.017$ due to Bonferroni adjustments).
*Discomfort scores significantly different between G5 and G95 ($p < 0.05$).
**Discomfort scores significantly different between G5 and G95 ($p < 0.01$).

Table 4: Discomfort assessment according to vehicle dimensions and anthropometry.

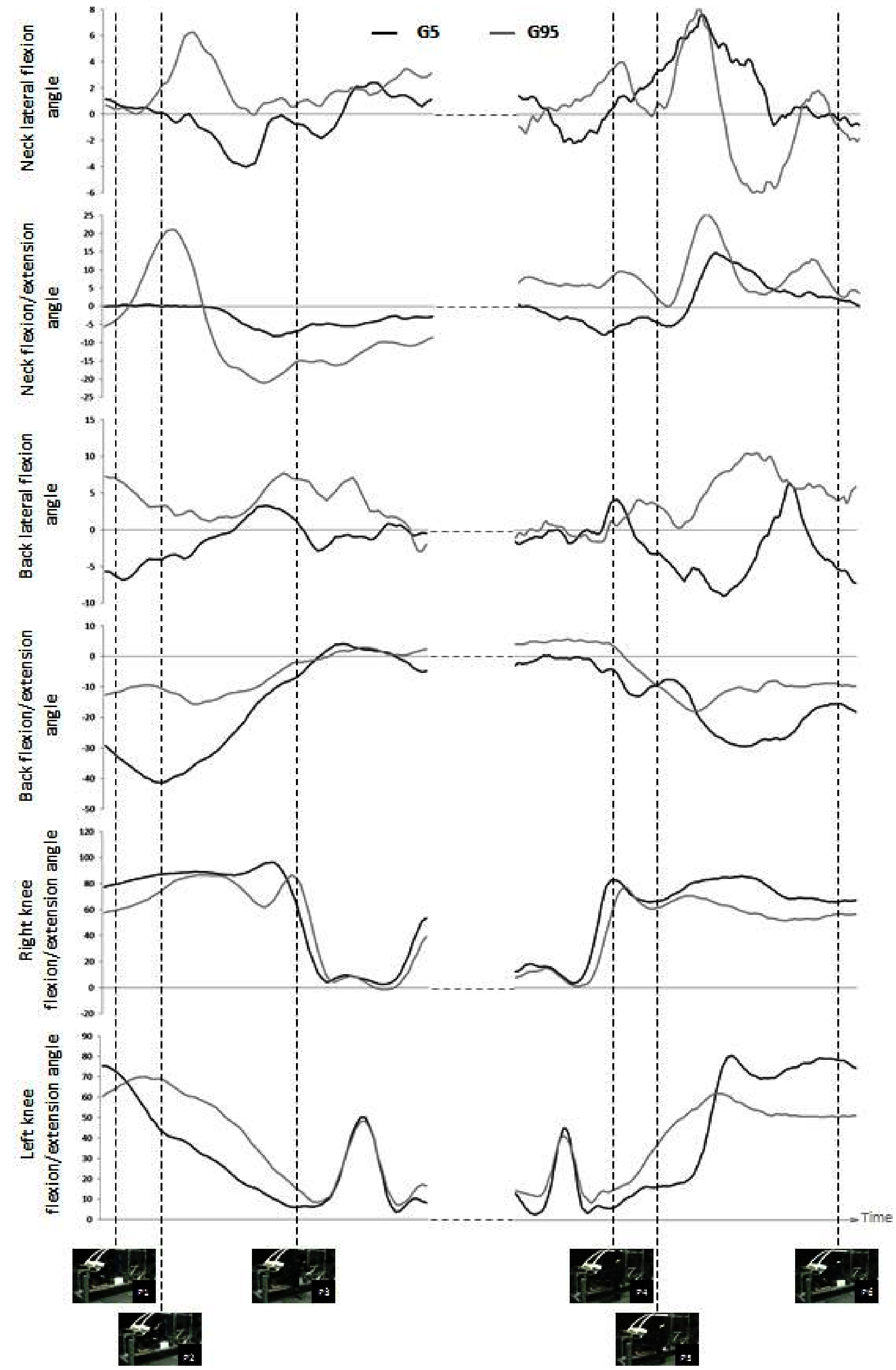

Figure 4: Mean joint angles of G5 and G95 groups during egress and ingress motion (positive values correspond to left side for lateral flexion angles).

discomfort experienced by participants from the G5 group at SH3. This may be explained by the fact that participants associated to the 5th percentile in height felt too high when going out of the vehicle. Indeed, SH3 corresponded to 510 mm height between the floor and the seat, the edge of the vehicle being settled at 250 mm (Figure 1b), and G5 participants are associated to 399 mm height between the popliteal fossa and the floor [27]. Thus this height difference may have impacted the general feeling of balance for the G5 group. Moreover, they probably had more effort to do during ingress motion as the center of gravity had to be lifted more upwards, and there were no handles on the framework in the physical mock-up (Figure 1b). Thus this SH has to be avoided for G5 participants. As it was not the case for G95 participants, an adjustable SH between SH1 (= 580 mm) and SH3 (= 760 mm) may be proposed for the design of the mail delivery vehicle (Figure 1a).

Discomfort score differences		Global: Cohen's *d* index	Global: Recommended sample size (per group)	Between G5-G95 groups	Between G5-G95 groups: Cohen's *d* index	Between G5-G95 groups: Recommended sample size (per group)
SH	SH1-SH2	0.26		SH1	0.11	
	SH1-SH3	1.25	12	SH2	0.14	
	SH2-SH3	1.06	16	SH3	2.56	4
HH	HH1-HH2	0.32		HH1	1.08	15
				HH2	0.14	
HW	HW1-HW2	0.14		HW1	1.74	7
	HW1-HW3	0.72		HW2	0.16	
	HW2-HW3	0.63		HW3	1.42	9

Table 5: Cohen's d index and corresponding recommended sample size for global and between-group comparisons in discomfort scores.

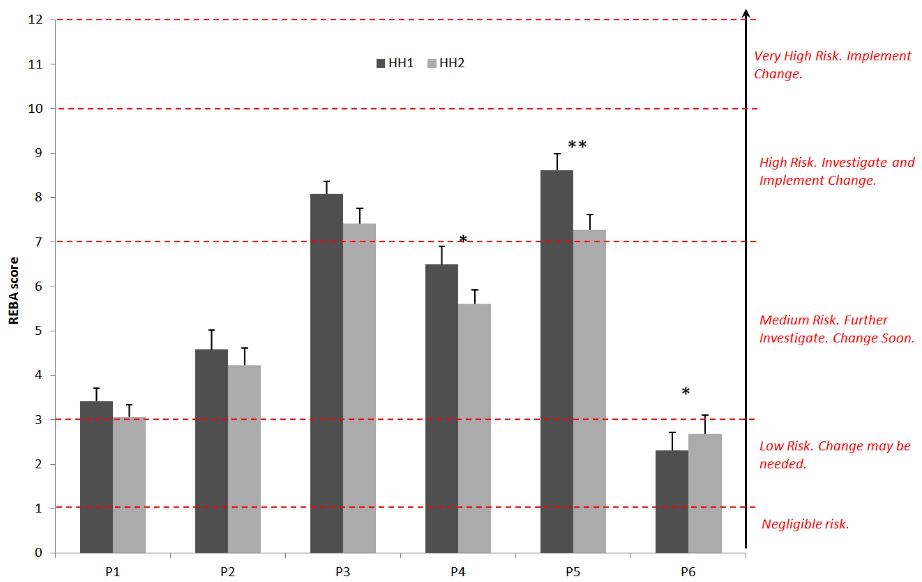

Figure 5: Mean REBA scores according to HH (HH1, HH2) at each posture (*: $p < 0.05$; **: $p < 0.01$).

Influence of HH

Concerning REBA scores depending on HH, they were all significantly higher for HH1 compared to HH2 (Z= -3.74, $p < 0.001$). This would mean that participants were less at risk with a high height of the headlining. Indeed, participants would have more space in the vertical axis to go in and out of the vehicle and subsequently lower joint angles would have been necessary to perform egress and ingress motions. This assumption has been confirmed by the joint angles analysis, i.e. neck and back flexion angles were 5° higher in amplitude during the HH1 compared to the HH2 condition. This might be especially true for participants associated to the 95th percentile in height. Indeed, tall participants entering a medium-sized car flex the head on the trunk while short participants perform an extension [15]. This flexion movement is also noticed when tall participants exit the vehicle [34]. This motor strategy was confirmed by the biomechanical analysis of joint angles in the current study (Figure 4). Indeed, participants from the G95 group highly flexed their head on the trunk while entering and going out of the mock-up, compared to participants from the G5 group who adopted a more upright trunk posture. This increased amplitude of the neck joint angle has subsequently influenced the REBA score of G95 participants. This motor behavior might be due to the fact that tall participants have a larger space available between the seat and the steering wheel [17,34].

The postural analysis revealed that postures 3 and 5 were the most risky, and posture 6 was the least awkward with HH (Figure 5). REBA scores at each posture decreased with the increase of the HH, except for posture 6. Nevertheless, REBA scores for this posture were both in the "low risk" area. HH had a significant impact on REBA scores for posture 4 (Z = -2.18, $p<0.05$), posture 5 (Z = -3.13, $p<0.01$) and posture 6 (Z = -2.38, $p<0.05$).

Concerning discomfort scores, there was a significant interaction of HH with anthropometry ($\chi2(3) = 18.33$, $p< 0.001$). This interaction was due to significant differences between discomfort scores obtained by G5 and G95 with HH1 (Z = -2.63, $p<0.002$ due to Bonferroni corrections), scores obtained by G5 with HH1 and G95 with HH2 (Z = -2.11, $p <0.01$), scores obtained by G95 with HH1 and G5 with HH2 (Z = -2.9, $p<0.002$), and scores obtained by G95 with both HH1 and HH2 (Z = -2.92, $p<0.002$). These results are in line with REBA score analysis: participants were more at ease with a high HH, especially for tall participants. Thus, we concluded that a HH of 1260 mm appears less suitable than 1360 mm for the design of the future vehicle.

Influence of HW

Differences of discomfort scores with HW were significant after running a Friedman test ($\chi2(2) = 13.21$, $p = 0.001$). There was a statistically significant increase in perceived discomfort between HW1 and HW3 trials (Z = -3.23, $p < 0.017$ due to Bonferroni corrections), and between HW2 and HW3 trials (Z = -2.62, $p < 0.017$). Thus, REBA and discomfort scores appeared higher for the HW3 condition (= 750 mm). This was particularly true for postures associated to the end motion of egress (P3) and the beginning movement of ingress (P4 and P5), where the headlining was more in interaction with the participant. Moreover, the highest dimension of the HW had a special impact on the tallest participants (G95), whether it be for the REBA score or the discomfort score. This might be explained by the fact that a high HW tended to create a large envelope around the passenger compartment, enforcing tall participants to bend so as to get in and out of the vehicle. This statement is in accordance with the fact that a large sill width of passenger compartment may increase the risk of adverse events, especially during egress [35]. We thus concluded that a HW of 750 mm (HW3) has to be avoided.

Interaction of HH and HW

There was a significant interaction of HH vs HW on discomfort scores ($\chi2(5) = 19.05$, $p < 0.01$). This interaction was due to significant differences between scores obtained with both HH1 and HH2 for HW1 ($Z = -2.14$, $p < 0.005$ due to Bonferroni corrections), scores obtained with both HW2 and HW3 for HH1 ($Z = -2.43$, $p < 0.005$), scores obtained with both HH1-HW3 and HH2-HW1 ($Z = -2.8$, $p < 0.005$), scores obtained with both HH1-HW3 and HH2-HW2 ($Z = -2.5$, $p < 0.005$), scores obtained with both HW1 and HW2 for HH2 ($Z = -2.43$, $p < 0.005$), and scores obtained with both HW1 and HW3 for HH1 ($Z = -2.7$, $p < 0.005$). Although this statistical analysis has to be carefully considered due to the small number of participants, the interaction effect of HH and HW gave more insight for the definitive selection of the vehicle dimensions. Although this interactive effect was not significant for REBA scores, the combined analysis of discomfort scores revealed that participants felt more discomfort for the HW2 condition (score = 11.22 ± 10.13) than for the HW1 condition (score = 5 ± 3.09) with the HH2 dimension. Thus, we concluded that a HW of 300 mm appeared more appropriate for this particular design.

Limitations

In the present study, the objective assessment was performed using the REBA scoring method [28]. However, this scoring system may be questionable according to limited original epidemiological data [36]. Moreover, in the current study, a semi-objective REBA assessment method has been performed by combining goniometers data and subjective evaluation of an ergonomist from video replaying, at six key postures. Inertial motion capture systems may help to perform more objective and extensive ergonomic analysis continuously [37-39]. Moreover, it has to be noted that differences in REBA scores appeared small in the current study (Table 3). Although some of these REBA scores were significantly different from one condition to another, these differences were more meaningful when it permitted to decrease or increase one level of risk in the REBA exposure classification Posture 1 in Figure 5.

Moreover, each participant was asked to adapt to a fixed dimension during the experiment (three SH, two HH and three HW) rather than let them select their own suitable dimension. Although the psychophysical approach would have been suitable to the aim of this study (e.g. [40]), the MobyPost project requirements imposed to identify one dimension for each parameter. Thus a universal approach was adopted in the current study [41]. It has to be noted that the width of the entry space into the cab has not been tested in the current study, even though it may appear as a critical dimension to assess egress/ingress motion when designing a car. Moreover, no measure of efficiency, e.g. egress/ingress time, was collected in this study. To be consistent with the International Standard ISO 6385 [21] which defines main ergonomic principles in the design of work system, participants were half women and half men. They were also associated to the 5th percentile and the 95th percentile in height, respectively. Indeed, in a mixed total population, the 5th through 95th percentile range covers 90% of a working population, i.e. the top 5% of men and bottom 5% of women are excluded, but because half the sample are men and half are women, 5% of the total sample are excluded [42]. Even though, including a broader range of anthropometric measurements, i.e. from the 1st to the 99th percentile, might appear necessary especially when dealing with security of industrial products [5,43]. However, the fact that workers were mail carriers recruited in the same geographical area, and the amount of time the research unit had to perform its ergonomic analysis, considerably reduced the number of participants. Thus the current study does not pretend to be as robust and representative as a genuine laboratory experiment, but it describes a valuable case-study applied into an industrial process.

Practical implications

The present mock-up costed 6000 euros in material (aluminum profiles, screws and bolds, wood structures, etc.) to which a package of 450 hours of development ensured by our mechanical engineers has to be added. The use of the physical mock-up turned out to be essential to make every involved actor aware of the practical implications of any dimension decision. Indeed, we also used the physical mock-up as a tool to express end-users comfort during project meeting where all the partners were in the same room. We thus were able to make mechanical designers feel the difference in the ease to get in and out of the cab if one decided to, for instance, increased SH. In the same way, the fact of using a physical mock-up during the user testing enabled to add subjective comfort evaluation to our dimensional recommendations.

More specifically, concerning the dimensions we finally obtained on the vehicle prototype, some constraints force the mechanical designers to modify the recommended dimensions. For instance, the recommended SH had to be adjustable between 580 and 760 mm. But it was fixed to 690 mm on the end vehicle due to a modification in the location of the batteries. Concerning the HH, we recommended a minimum of 1300 mm and the taken measures on the end vehicle were 1360 mm. Finally, for the HW, our recommendation was respected since we recommended a maximum of 750 mm where we measured 720 mm on the end vehicle.

Conclusion

The aim of this study was to define the dimensions of an innovative vehicle dedicated to mail delivery using an ergonomic approach. Thus, the influence of different passenger compartment dimensions (SH, HH and HW) on an estimation of the risk to develop musculoskeletal disorders and the discomfort perceived by mail carriers, with different anthropometric characteristics, has been assessed while performing egress and ingress movements into an adjustable physical mock-up. This ergonomic analysis allowed defining suitable dimensions for the design of the future vehicle, i.e. an adaptive SH between 580 and 760 mm (from the ground), a HH of 1360 mm (from the ground) and a HW of 300 mm.

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References

1. Bryant S, Wrigley C (2014) The drive towards user-centred engineering in automotive design. Proceedings of the 19th Academic Design Management Conference.
2. Veryzer RW, Borja de Mozota B (2005) The impact of user-oriented design on new product development: An examination of fundamental relationships. J Produc Innov Manag 22: 128-143.
3. ISO 9241-210 (2010) Ergonomics of human-system interaction - Part 210: Human-centred design for interactive systems.
4. Pheasant S, Haslegrave CM (2016) Bodyspace: Anthropometry, ergonomics and the design of work. CRC Press.
5. ISO 15537 (2004) Principles for selecting and using test persons for testing anthropometric aspects of industrial products and designs.
6. Panero J, Zelnik M (2014) Human dimension and interior space: a source book of design reference standards. Watson-Guptill.
7. Demirel HO, Duffy VG (2007) Applications of digital human modeling in industry - Digital human modeling. Springer Berlin Heidelberg.
8. Paul G, Reed M, Wang X (2012) Digital human modelling for vehicle design and manufacturing. International Journal of Human Factors Modelling and Simulation 3.
9. Chaffin DB, Erig M (1991) Three-dimensional biomechanical static strength prediction model sensitivity to postural and anthropometric inaccuracies. IIE Transactions 23: 215-227.
10. Reed MP, Parkinson MB, Klinkenberger AL (2003) Assessing the validity of kinematically generated reach envelopes for simulations of vehicle operators. Proceedings of the Society of Automotive Engineers Digital Human Modeling Conference.
11. Ziolek SA, Nebel K (2003) Human modeling: controlling misuse and misinterpretation. SAE Transactions 112: 623-628.
12. Pewinski W, Esquivel A, Ruud J, Stefani M, Barbir A (2005) Jack e-factory correlation to real world seating reach and effort applications. SAE Technical Paper.
13. Raschke U, Kuhlmann H, Hollick M (2005) On the design of a task based human simulation system. SAE transactions 114: 760-766.
14. Lamkull D, Hanson L, Ortengren R (2008) Uniformity in manikin posturing: a comparison between posture prediction and manual joint manipulation. Intern J Human Factors Modelling Simulation 1: 225-243.
15. Andreoni G, Rabuffetti M, Pedotti A (2004) Kinematics of head-trunk movements while entering and exiting a car. Ergonom 47: 343-359.
16. Ait El Menceur MO, Pudlo P, Découfour N, Bassement M, Gillet C, et al. (2006) An experimental protocol to study the car ingress/egress movement for elderly and pathological population. Proceedings of the European Annual Conference on Human Decision Making and Manual Control.
17. Causse J, Wang X, Denninger L (2011) Effects of roof height on car ingress/ egress movement. Proceedings of the First International Symposium on Digital Human Modeling.
18. Aromaa S, Viitaniemi J, Helin K, Vento A (2014) Ergonomic evaluation of cab design employing digital and physical mock-ups. Advances in Ergonomics In Design, Usability & Special Populations: Part I 16: 410.
19. Sang CL, Ren JD, Liu YQ, Mi MD, Li SH, et al. (2013) Development Of An Adjustable Physical Mock-up Used For Design Validation Of Passenger Car Ergonomics And Interiors. Advanced Materials Research 650: 698-704.
20. Wall K, Tomaszek-Staude W, Poeschl S, Doering N (2014) State of the art barriers in validation of digital mock-ups in immersive virtual environments. Proceedings of the 58th Ilmenau Scientific Colloquium.
21. ISO 6385 (2004) Ergonomic principles in the design of work systems.
22. Dubuisson S (1995) La conception en design. Etude des formes de collaboration et de communication dans la conception design des objets nouveaux - Le communicationnel pour concevoir. Europia Production.
23. Bentley TA (1998) Slip, trip and fall accidents occurring during the delivery of mail. Ergonomics 41: 1859-1872.
24. Bentley TA, Haslam RA (2001) Identification of risk factors and countermeasures for slip, trip and fall accidents during the delivery of mail. Applied Ergonomics 32: 127-134.
25. Reinert F, Lucio C (2012) Postmen activity's analysis. Work 41: 5603-5604.
26. Theurel J, Theurel A, Lepers R (2012) Physiological and cognitive responses when riding an electrically assisted bicycle versus a classical bicycle. Ergonomics 55: 773-781.
27. Motmans R (2005) Dinbelg 2005: Body Dimensions of the Belgian Population [online]. http://www.dinbelg.be
28. Hignett S, McAtamney L (2000) Rapid entire body assessment (REBA). Applied ergonomics 31: 201-205.
29. Lempereur M (2006) Simulation du mouvement d'entrée dans un véhicule automobile. Doctoral dissertation, Université de Valenciennes et du Hainaut-Cambresis.
30. Chateauroux E (2009) Analyse du mouvement d'accessibilité au poste de conduite d'une automobile en vue de la simulation. Doctoral dissertation, INSA de Lyon.
31. Shen W, Parsons KC (1997) Validity and reliability of rating scales for seated pressure discomfort. Inter J Indus Ergonom 20: 441-461.
32. Zhu W (2016) p< 0.05,< 0.01,< 0.001,< 0.0001,< 0.00001,< 0.000001, or< 0.0000001…. J Sport Health Sci 5: 77-79.
33. Cohen J (1988) Statistical power analysis for the behavioral sciences. (2nd edn), NY: Psychology Press.
34. Causse J, Wang X, Denninger L (2012) An experimental investigation on the requirement of roof height and sill width for car ingress and egress. Ergonom 55: 1596-1611.
35. Crizzle AM, Vrkljan BH, Kajaks T, Gish J, Fleisig R (2014). A Systematic Review of Driver Ingress and Egress Using Passenger Vehicles: Considerations for Designers. J Ergonom.
36. Li G, Buckle P (1999) Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonom 42: 674-695.
37. Vignais N, Miezal M, Bleser G, Mura K, Gorecky D, et al. (2013) Innovative system for real-time ergonomic feedback in industrial manufacturing. Appl Ergonom 44: 566-574.
38. Peppoloni L, Filippeschi A, Ruffaldi E (2014) Assessment of task ergonomics with an upper limb wearable device. Proceedings of the IEEE 22nd Mediterranean Conference of Control and Automation.
39. Battini D, Persona A, Sgarbossa F (2014) Innovative real-time system to integrate ergonomic evaluations into warehouse design and management. Comp Indus Eng 77: 1-10.
40. Wang X, Trasbot J (2011) Effects of target location, stature and hand grip type on in-vehicle reach discomfort. Ergonom 54: 466-476.
41. Goldsmith S (2000) Universal design: a manual of practical guidance for architects. Routledge.
42. Marklin RW, Saginus KA, Seeley P, Freier SH (2010) Comparison of anthropometry of US electric utility field-workers with North American general populations. Human Factors: J Human Factors Ergonom Society 52: 643-662.
43. Hsiao H, Whitestone J, Bradtmiller B, Whisler R, Zwiener J, et al. (2005) Anthropometric criteria for the design of tractor cabs and protection frames. Ergonom 48: 323-353.