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STUDY OF HUMAN ACCESSIBILITY: COMPARISON BETWEEN PHYSICAL TESTS AND NUMERICAL SIMULATION RESULTS

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1. Introduction

In the field of universal design, taking into account the physical characteristics of the target population during the design process is essential. However, human variability causes difficulty to meet the requirements of comfort and security of a certain percentage of the user population. That's why human factors engineering allows to optimize the interactions with the user systems, considering the human body variability of population. Physical ergonomics allows to study interactions among humans and other elements of a system, to create an environment that is well-suited to a user's physical requirements. Many tools and practices are in common use today to assist in basic assessments of accommodation, and indicate to the engineer how to design for the variability in body dimensions (or anthropometry), capability and age, in the target user population [Roebuck 1995]. A commonly used approach is the "population models", where a group of individuals representing the target-user population interacts with a real prototype, involving robust assessments and consideration of subjectives sources of variability (as preferences, comfort…), difficult to take into account without interaction. However, such a method involves a lengthy and costly process (creation of prototypes, users population…), especially if it is necessary to make changes to the product.
To avoid building expensive physical mock-up, the designer can use anthropometrics database (e.g. ANSUR [Gordon et al. 1989], NHANES [Centers for Disease Control and Prevention 1994]), where body dimensions are generally used to fit the relevant product dimensions. Thus, several methods based on these anthropometric data [Committee 2004] are used to design adapted products and assess the degree of accommodation. Existing database may be chosen as the reference population and use directly ("boundary mannequins"...) [Drillis and Contini 1966], [Garneau and Parkinson 2010] or through regression techniques ("population model", hybrid approaches"...) [Reed and Flannagan 2000], [Garneau and Parkinson 2007], [Holler 2010], generally used in univariate case study to determine the appropriate allocation of adjustability to achieve a desired accommodation level. Although numerical methods are faster and less expensive than building prototypes, only considering human bodies with their static anthropometric caracteristics may be not always representative of the target user population and involve inaccuracies during ergonomic evaluation between individual and the environment [Moroney and Smith 1972]. Indeed, these methods are generally used in univariate case study (to determine the appropriate allocation of adjustability to achieve a desired accommodation level), where most problems are multidimensional. Additionally, anthropometric databases often consist of specifics surveys on target profiles (military...) and typically provide only very limited information concerning for instance children or people who are older or disabled, which can be problematic to perform assessments for specific populations [Marshall et al. 2002]. Moreover, unlike physical tests, this approach does not take into account the biomechanical proprieties (as

muscles compliance for example). Although some numerical models exist to model and quantify the Muscolo-sceletal properties of human body parts (e.g stretching effects), numerical simulations may not take into account variables that could influence the ergonomic evaluation (e.g the influence of the external environment on the subject, the physical skills or the attitude and the cognitive processes specific to each one). That is why, although the use of digital data allows to avoid to perform experimental tests and building prototypes, methods based on this principle still pose questions about the ease of use and reliability compared to reality. The aim of this study is to highlight differences of results that can rapidly occur when performing ergonomic assessments through real experiments and numerical estimations. So, we propose to perform an accessibility study for a "simple" univariate case and to compare results obtained experimentally with those obtained by calculation using a simple numerical model (using raw anthropometric data).
In a first test, 40 subjects (25 males and 15 females) were asked to perform accessibility tests (reach specific points) simulating a generic task that could be applicable for different real reach situations. This first experiment is called the "discret test". Then, subjetcs were asked to performed the "continuous test" consisting to directly draw their reach envelope. Both tests were carried out in standing position with the body fixed (trunk and foot fixed), then with the upper body free (trunk mobile and foot fixed). Experiments and results obtained are presented and discussed below.

2. Comparative study

In this part, the four conducted experiments are presented. Tests are implemented to evaluate accessibility based on physical capacity and characteristics of each subject, trying to not including, as far as possible, sources of variability such as the notions of preference (e.g differences of adjustments of a seat heigth for two subjects with similar body dimensions). The aim being to make an objective comparison with the numerical model, without including variables in the comparison that will not be related to the physical characteristics of the individul and to the achievement of the task.

2.1 Methodology

This paper considers two ways to assess accessibility in which experimentation and database approach are applied in accessibility evaluation (Figure 1). We focus on the accessibility of the upper body. A population of various people was selected. They are asked to participate to two different tests of accessibility (reached envelope): discret test A and continuous test B. In the same time, some of there physical characteristics are measured to create an anthropometric database. These database aim to be used as input of the two numerical simulations to determine the theoretical reached envelope. The two experiments proposed, each time realized physically and numerically, aims to highlight the differences of experimental results in comparison of real accessibility, and so to verify if the numerical simulation of the upper body reach envelope might be considered as realistic.

2.2 Subjects and anthropometric measurement

The experiments were conducted with 40 adult volunteers, French students or teachers of the Ecole Centrale de Nantes. In order to create a database of measurements, four anthropometric characteristics were measured for each of them (Figure 2), namely the stature, the shoulder height, the shoulder width and the arm length (Table 1). Twenty five males and fifteen females were sampled in the study, covering a wide spectrum of physical characteristics, from 1482 mm for the smallest stature, to 1930 mm for the highest.

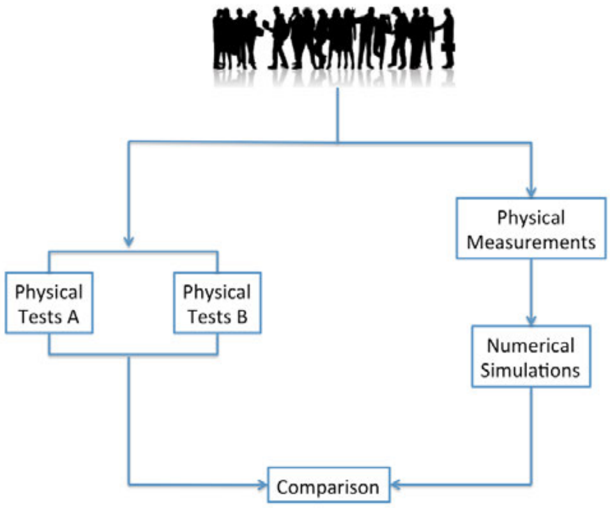

Figure 1. Synopsis of the study

2.3 The A test

Experiment A allows to simulate realistic arm accessibility situations through interaction with physical points (switches).

2.3.1 Description and physical realization

Principle: *Accessibility to switches located in front of an individual and positioned on a vertical plate (effect of the body position while reaching).* A plate is positioned on a vertical wall with the aid of two adjustable vertical axes for precise positioning of the bottom plate at shoulder height *He* (Figure 3). Reach measurements are made relatively to a body reference point (shoulder joint) and to a measurement apparatus point (bottom of the plate). The subject is positioned in the center of the plate with the feet fixed regarding the floor (a position sensor is positioned under the heels of the subject indicating if the feet are off the ground or not). For each individual, the reached switches are identified and noted in a table in order to draw the reach envelop. A total of 84 switches can be reached on the plate, which constituted 168 measurement points (two positions for each switch). With a view to ease of notation and understanding, participants are asked to touch the switches by color strips (with his left or right arm according the side), giving 12 black, 32 white, 44 green, 46 blue and 34 red reachable points. The device is designed to fit at shoulder height for a wide range of human physical characteristics (designed from 2.5th and 97.5th percentile for women and man stature of ANSUR database), allowing to perform the tests for a large user population. Because most anthropometric data presented in databases represent nude body measurements and to permit reliable comparison with database approach, experiments are performed with light clothing (nude dimension and light clothing being regarded as synonymous for practical purposes). For both tests A1 et A2, the task demands can be defined as "reach switches with at least one finger and push it".

Table 1. Anthropometric characteristics measured for each participants, with values in mm

Individuals	Gender	Stature	Shoulder height	Shoulder width	Arm length
1	M	1735	1485	470	750
2	F	1705	1450	430	730
3	F	1482	1240	420	640
⋮	⋮	⋮	⋮	⋮	⋮
40	M	1715	1420	460	710

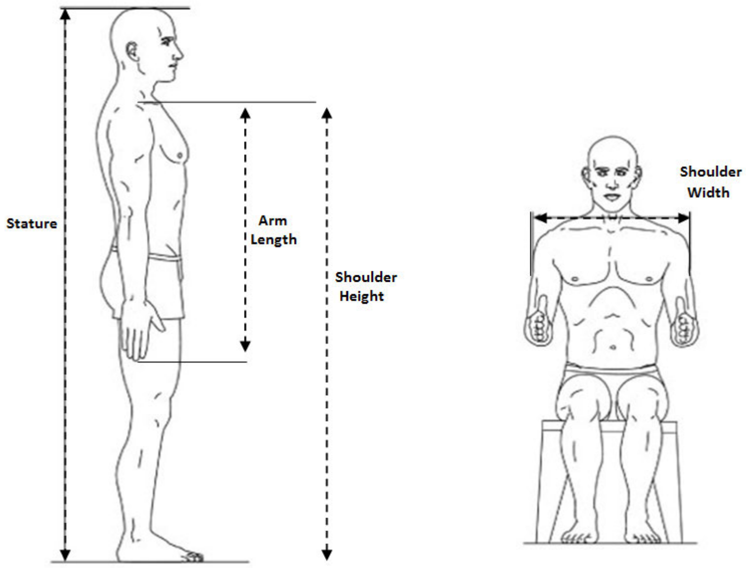

Figure 2. Anthropometrics characteristics measured

Test A1: The subject keeps the feet fixed to the floor and the body must stay fixed (spinal column axis) relative to the vertical axis of the center of the plate, and reaches switches one arm at a time.
Test A2: The subject keeps the feet fixed to the floor but is allowed to twist (changing the position of the upper body) to reach the switches, one arm at a time.

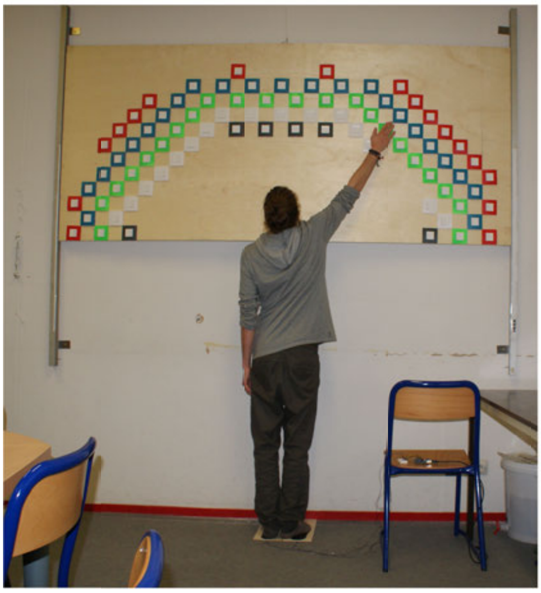

Figure 3. Discret experimental test A1 (the subject is reaching switches on the right of the plate with his right arm)

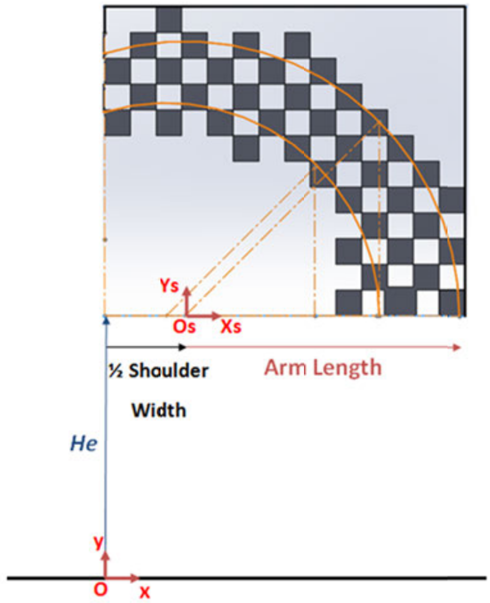

Figure 4. Definition of accessibility from anthropometric data (the reached switches are those included within the envelope)

2.3.2 Numerical simulations (tests A)

Reached switches calculation: *The objective is to compute the reached switches according to the anthropometric characteristics recorded during experimentations (experimental database).* The reach envelope is defined by a circle arc, with the arm length as radius and the position of the shoulder Os as rotation point (Figure 4). So, knowing the coordinates of the switches on the plate, the theoretically reach points computed from arm length and shoulder width can be defined. Reach envelope is defined

by assuming that the arm makes a perfectly circular arc with the shoulder as the center of rotation. Moreover, as the database usually provide data for only one arm, we use the value of the right arm and admit that both are perfectly symmetrical. Knowing the switches coordinates on the plate and the anthropometrics characteristics of individuals, a programme is implemented (using Matlab R2012b) allowing to automatically determinate which switches are theoretically reached by the arms. The realisation of experimental tests A1, A2 and numerical calculations provide, for each participant:
_ Switches reached with the fixed body
_ Switches reached with the upper body flexible
_ Switches that should have been reached according to the model used

2.4 Experimental tests B

2.4.1 Description and physical realization

Objective: *Marking of the boundaries of arm reach of an individual in standing posture.*
The participant stays in front of an erasable marking device, positioned on a vertical wall on which he must draw his reached envelope (Figure 5). Then, a photo of the drawing is taken and treated thanks to a Matlab program to accurately determine the area of the envelope (Figure 6). As tests A, reach envelope of tests B are constructed considering one-handed operation with fixed foot, and movements or not of the torso.
Note: reach design dimensions or envelopes for design use should be constructed considering grasp requirements which may affect the functional reach envelope. Fingertip touch resulting in the largest reach dimensions appropriate for touch controls, envelopes are marked to define the task as "finger touch" function (one finger touches an object without holding it) in order to avoid as much as possible a grasp effect (reducing the reach envelope).
Test B1: The subject keeps the feet fixed to the floor and the body fixed (spinal column axis) relative to the vertical axis of the center of the plate, and marks his reach envelop with both arms simultaneously.
Test B2: The subject keeps the feet fixed to the floor but is allowed to twist (changing the position of the upper body) to marks his maximum reach envelop one arm at a time.

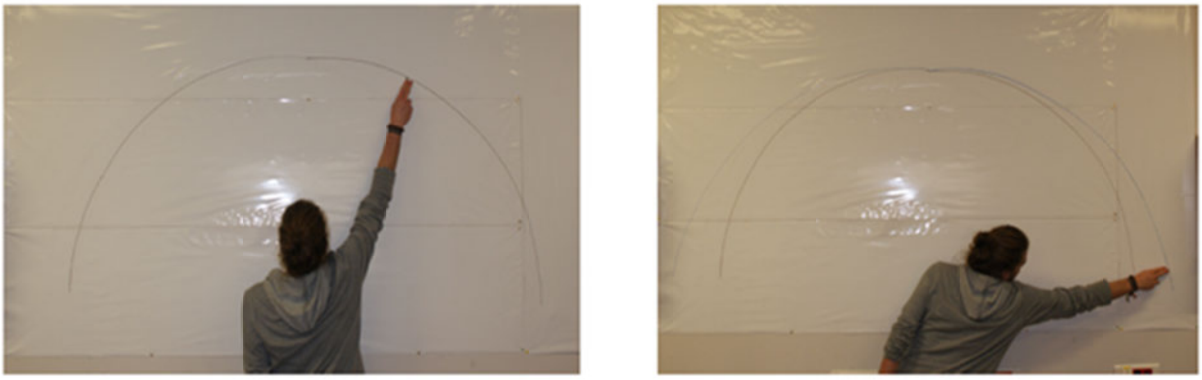

Figure 5. Continuous experimental test B1 (left) with the feet and the body fixed, and test B2 (right) with the feet fixed and the upper body in movement

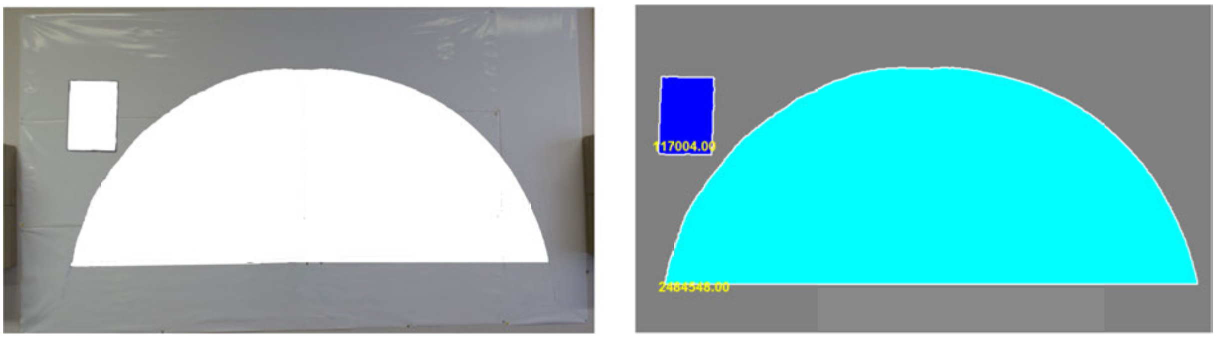

Figure 6. Image processing using matlab. Bright space represents the reach envelope area drawn by the participant. The dark area (rectangle) represents the paper sheet used as repository to calculate areas from pixels to square meters

2.4.2 Numerical simulations (tests B)

The objective is to determine the reach envelope area of a subject based on his static anthropometric characteristics, such as might be found in a database. That is, the theoretical reach envelope area for each participant (defined by envelopes Figure 7) is calculated using the arm length (iB) and the shoulder width (ih) (all other quantities being calculated from these values). Reach envelopes should be constructed considering the shoulder (arm rotation point) as reference point in the envelope calculation to determine the different arc circle areas. So, the total area reached on the wall by the arms of the individual is numerically simulated by Eq.1, where both arm lengths are considered as the same. Area A4 is a common part for both arm; so to avoid redundancy in the calculations, this area is not taken into account in the definition of the total envelope.

$$A_{totale} = 2.(A_1 + A_2 + A_3) = 2.\int_i^B \sqrt{B^2 - x^2}dx + 2.\int_i^h \sqrt{B^2 - x^2}dx + h.y_{Hi} \quad (1)$$

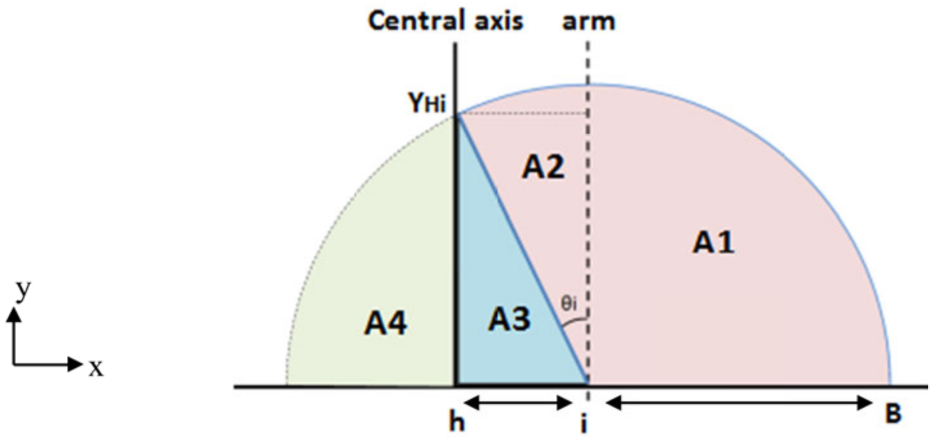

Figure 7. Calculation of reach envelope areas

3. Results and discussion

Each participant was asked to perform the four experiments. Results are collected, providing for each of them the experimental results obtained with "fixed" body, with flexible upper body and theoretically from numerical model, in the case of discret tests (Table 2) and continuous tests (Table 3). Figure 8 and 9 represent the results of tests A1, A2, B1 and B2 measured from experiments, and the numerical calculations plotted against stature for the 40-member sample, with regression line.

Table 2. Numbers of reached switches for each participants, measured from experiments A1, A2 and numerically calculated. ΔA1 and ΔA2 are respectively the differences of reached switches between the calculations and experiments

Individuals	1	2	3	4	...	40
Reached switches for A1 test	79	67	30	86	⋯	71
Reached switches for A2 test	107	102	52	109	⋯	97
Reached switches numerically calculated	81	59	30	91	⋯	60
$\Delta A1$	2	-8	0	5	⋯	-11
$\Delta A2$	-26	-43	-22	-18	⋯	-37

Table 3. Reach areas for each participants, measured from experiments B1, B2 and numerically calculated. ΔB1 and ΔB2 are respectively the differences of areas between the calculations and experiments

Individuals	1	2	3	4	...	40
Reach areas for B1 test	1.13	1,06	0,85	1,26	⋯	1,22
Reach areas for B2 test	1.28	1,29	1,01	1,65	⋯	1,42
Reached areas numerically calculated	1,23	1,15	0,91	1,31	⋯	1,11
$\Delta B1$	0,10	0,08	0,05	0,04	⋯	-0,10
$\Delta B2$	-0,05	-0,15	-0,10	-0,34	⋯	-0,30

The aim of the experiments was to determine :
- the influence of the stretching of the body on the reach performances.
- the discrepancy between the numerical simulation and the real experiment.

Regarding Table 2, we notice first that the number of switches activated might be very different for the different subjects: from 30 to 105. It is very dependent of the stature: Pearson coefficient is 0.83 with the stature against 0.78 with the length of arms. The average standard deviations of the distributions A, A1 and A2 are respectively equal to 20, 21 and 23. We compare the significance of the stretching of the body. Results for A2 are obviously superior to A1 but the range is hight: an average increasing of 40% of switches. The second point is about the validation of our model. If we compare A1 to A from simulation, we find an average difference of 8 switches. Knowing that the switches are organized close one from the other, this difference is acceptable. But in the case of A2, this same average is 33. On the Figure 7, it can be seen a vertical translation between the linear regressions obtained from experimental data A1, A2 and calculated data A. As it might be expected, the model used is not adapted to body with a possible stretching.

The simulated data B and experimental data obtained through tests B1 and B2, plotted with respect to stature, are shown in Figure 8. The average standard deviations of the distributions B, B1 and B2 are respectively equal to 0.13, 0.13 and 0.17. This dispersion of the calculated data might be explained by the differences of anthropometry of subjects, accentuated by the fact that the male and female data are processed simultaneously, explaining the cloud of points obtained. For example, for a same height, the arm lengths can vary greatly from one individual to another, directly affecting the reach envelope, which is calculated from the value of arm length and shoulder width. The results obtained experimentally by tests B1 are quite close to those obtained theoretically, with a mean difference $\Delta B1 = (B_{calculated} - B1_{experimental}) = 0{,}05$. So, the reach areas measured from experiment B1 might be considered as acceptable in comparison to reality. However, as for the test A2, values for B2 are widely superior in comparison to those calculated, with a mean difference of $\Delta B2 = (B_{calculated} - B2_{experimental}) = -\ 0{,}234$. In general, it is observed that the values obtained experimentally are higher compared to numerical calculations from anthropometric data of individuals passing the tests. The results show the important error that the simulations (in common use for design) can provide to this extremely simple accessibility assessment.

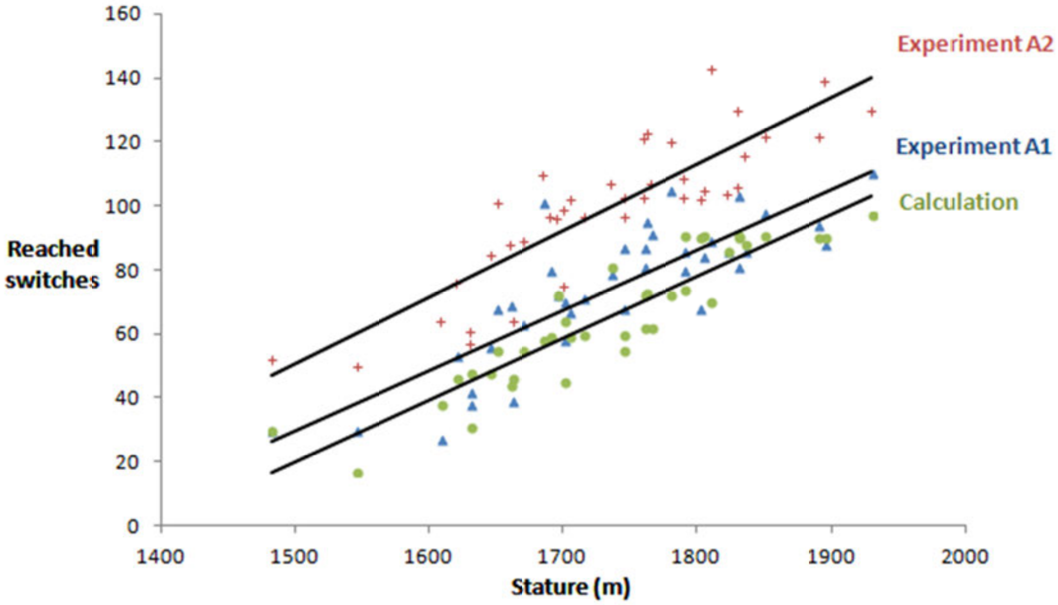

Figure 8. Results for A1 and A2 measured from experiments and from numerical calculations, with regression line

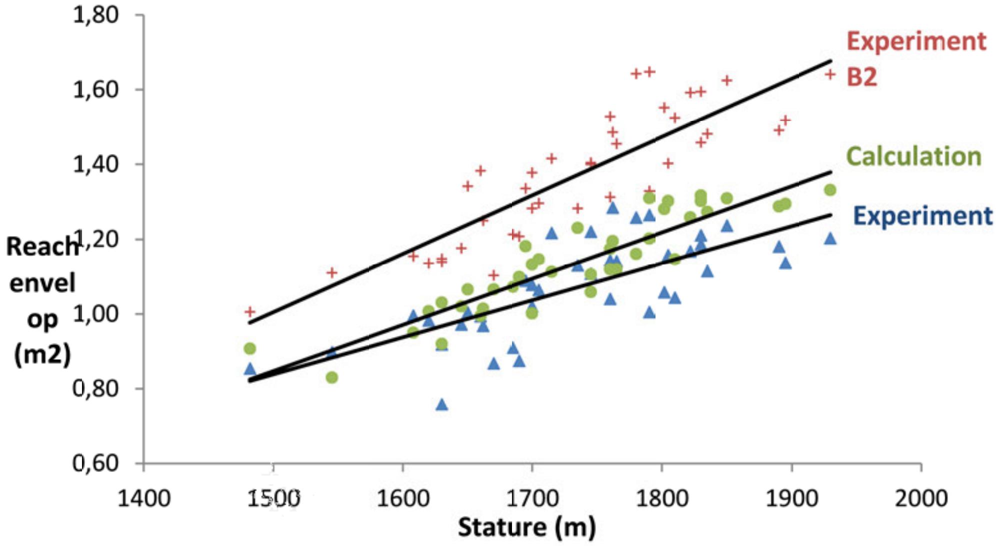

Figure 9. Results for B1 and B2 measured from experiments and from numerical calculations, with regression line

The tests A1 and B1 have allowed to show that in a fixed position, the results obtained by numerical method are quite close to the experiment. However, results from tests A2 and B2 have shown that numerical calculations varying greatly from the experiment. This is due to the fact that in this situation, accessibility is measured when the body is in motion and engaged in a physical activity (role of balance maintenance in limiting extreme reach capability). Indeed, the numerical model (which uses raw numerical data) being based on static anthropometry, it does not take into account the functional anthropometry induced by dynamic behaviour of the human body (stretch of muscle, body motion ...) intrinsic to real situations. These finding are consistent with other studies [Kroemer et al. 1990] involving more complex problem showing that reach limits are clearly dependent on the task, motion, and function to be accomplished by the reach action.

4. Conclusion/future work

This study showing that, even performing simple tests of accessibility, where theoretical results depending only on two dimensional parameters (shoulder width and arm length), the results obtained from the simple numerical model still differ significantly from reality. This can be explained by the fact that (1) stretching the body is far from be negligible in computing accessibility, and (2) the static model is not representative of the stretched body (functional anthropometry) but simply the right body (static anthropometry). Ignoring this variability can result in designs with too little adjustability (causing an inaccurate prediction of accessibility and a misfit design). Although experiments have been put forward to remove sources of variability unrelated to body dimensions, the experimental tests have demonstrated that the results obtained are also dependent on the behavior of each individual during the tests. For example for the test A2, while some stopped from the moment of a disconfort sensation was felt, others were performing the test to the maximum of their balance and flexibility limits. It is also interesting to highlight the impact of the functionality of the task at hand. Indeed, tests A involving physical touch points, experiment shows that in this case, even if experiments are implemented to minimize this behavior, participants were more engaged in the task and tried to move their upper body to reach switches. The differences in behavior highlights the impact of real-life situations (notions of objective and performance) through the physical points (switches) on the results. So, this shows that task demands (touching the switches) might affect reach characteristics and measures. In addition, this study involved young people (between 22 and 55 years) without disabilities or particular physical limitations, performing simple accessibility tests in experimental conditions allowing to be as much as possible closer to the numerical prediction model. So we can assume that for ergonomic evaluations involving populations with specific physical situations (children, elderly or disabled people ...) and for multidimensional situations, accessibility predictions using only such numerical model may lead to unrealistic results and unsuitable designs.

Initial study trials have shown the limits of the numerical simulation (based on raw anthropometric data) thanks to the real experiment (influence of the stretching of the body on the reach). This study highlights the importance of keeping a critical judgement on results that can be obtained by performing an ergonomic assessment, considering only the static dimensions of the different human body parts as variables. However, this method might be usefull (as a pre-assessment tool e.g) in collaboration with other ergonomics evaluations tools such as digital human modelling models, to provide a much greater understanding of the human behavior and population specific limitations, and to improve the ergonomic assessment process. That is why the aim for future work is to compare results with those obtained by performing the ergonomic assessment (accessibility tests) using the numerical model, in collaboration with human modeling software and virtual reality tools, enabling the designer to visualize and interact with the environment to perform ergonomics assessments as close as possible to reality. Moreover, an other perspective would be to explore models of body fatigue regarding the required task. In other words, although stretching the muscles can increase the achievement envelope, if such a movement is harmful to humans, these kinds of “extrem” skills have no interest in an ergonomic point of view.

A limitation of this work is that the presented comparative study is based on the total error between the experimental and theoretical (numerical) results. For Example for tests A, the difference is determined from the total number of switch reached by an individual compared to the numerical predictions. For test B, the difference is determined from the difference between the total reached area and the theoretical area. That is to say that this method does not allow to know if an individual reached more than expected on certain parts of the envelope and less on other (non-uniform envelope). That's why additional studies (not shown in this article) are being conducted to define and map the reached parts of the areas. Thus, by aggregating the results for each individual, the overall reach behavior can be modeled, allowing for example to determine parts of the area where errors are most critical (non-uniform reached).

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