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GRAPHIC 3D ERGONOMIC DATABASE IN EVALUATION OF VIRTUAL MODELS OF KITCHEN DESIGN/ADAPTATION FOR NEEDS OF HANDICAPPED PERSONS

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The paper presents a concept for the utilisation of anthropometric and biomechanical graphic 3D database of a motorically handicapped person using a wheelchair for purposes of analysis and assessment of kitchen space design. Contemporary tendencies in kitchen design or adaptation for disabled persons or senior citizens were discussed. Methodological assumptions as well as a test station for measurements of reach of arms and forces for a male disabled person sitting in a wheelchair were presented. The obtained results were arranged developing a virtual model of interactions between a handicapped user and kitchen equipment. Using the elaborated model, the field of vision and accessibility to a heating plate and cabinets in a standard and adapted kitchen were analysed. In conclusions, issues associated with kitchen adaptation were allocated into groups. Usefulness of the described database to perform digital simulations of various systems of technical facilities was emphasised. This approach allows appropriate arrangement of kitchen space in a way that takes into consideration unrealised needs of users.

Keywords: kitchen adaptation, disabled person, ergonomic database

Introduction

The demand for empirically verified and systematised design database taking into consideration specific requirements and possibilities of disabled persons has not been fulfilled so far. It should be emphasised that the designing process for handicapped persons is fairly complex due to the specificity as well as heterogeneity of requirements in the group of these persons [1] and that is why not all requirements of representatives of this group were satisfactorily defined and archived in the literature on the subject. In this article an attempt was made to determine and put in order requirements for kitchen internal design and furniture.

The aim of this study was to present one of many possibilities of utilisation of graphic, special ergonomic database. Such anthropometric and biomechanical database for a disabled person sitting on a wheelchair was developed within the framework of earlier investigations concerning the construction of advanced tools of virtual engineering [2]. It comprises an integral 3D model of arms' reaches as well as limiting forces of arms of the above-mentioned person. Ranges of allowable (safe) forces in the graphic 3D manipulation space can be transformed dynamically from ranges of limiting forces. This is a novel approach which is not found in the literature on the subject.

The study utilises the above-mentioned graphic database developed for ergonomic designing dedicated, in particular, to analyses in the virtual environment of space accessibility and safety of disabled persons on wheelchairs in kitchen design.

Contemporary trends in kitchen design or adaptation for disabled persons or senior citizens

Kitchen modelling in a systemic design approach or only design adaptation requires not only a development of an orderly set of furniture and technical equipment appliances combined by relationships in a given internal space. In addition, elasticity of modification and arrangement of kitchen equipment is also assumed. Systemic elements of universal kitchen design comprise all potential users of kitchens, especially, persons in old age as well as persons with locomotor and/or sensory dysfunctions. Such persons should

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themselves decide about their lives as well as about the kind of help of third persons (so called, independent life supported by others at one's own ergotherapy [3, 4, 5]). The following four basic activities can be distinguished in the process of kitchen utilisation: storage, preparation, cooking and washing up and, sometimes, also consumption of meals. The above activities are performed using technical equipment (refrigerator, cooker, sink) and furniture typical for them. The distribution of furniture and equipment should conform to the frequency of their utilisation and be connected with transport routes in technological pathways.

When planning work stations in the kitchen adapted to senior citizens, persons on wheelchairs as well as other handicapped persons, it is important to optimise construction solutions of furniture and other kitchen equipment taking into consideration functional (accessibility, convenience and utilisation safety) and aesthetic criteria. When designing a technological sequence, it is necessary to remember that the most comfortable position during kitchen work is when a person faces a given piece of equipment. Frequently, it is recommended that the involved disabled person on wheelchair should participate in the work of the team designing the kitchen. A kitchen for disabled persons moving on a wheelchair should have a slightly larger area to allow additional space for manoeuvre (150x150 cm) as well as increased storage space for the indispensible things to the height of 70-100 cm (cabinet for baskets) [6].

Thanks to special, disability-friendly solutions, it is possible to modify both the structure and arrangement of typical furniture [7]. Trends in the design of universal kitchens have undergone considerable changes in recent years following new ideas concerning internal structure of apartments, observed increase of kitchen area as well as the introduction into common use of novel household technical equipment.

Bearing in mind adaptation costs of an old apartment [8], it is much better to take into consideration possibilities of its adaptation already in the phase of its design. In 1996, an assessment was performed of adaptation costs of a typical M4 flat (3 rooms, kitchen, hall, bathroom with toilet) including elimination of barriers for a person with a dysfunction of lower limbs which was estimated at 46 000 PLN (about 11 500 €). The above costs included supply of new equipment as well as building-construction works together with changes in the technological pathway in the kitchen (electric cooker, sink, furniture with lowered cabinets, worktops and cupboards). Earlier FMEA analysis of causes and results of defects in an integration apartment indicated the following three most common shortcomings of a kitchen for users of wheelchairs:

- Impeded movement on a wheelchair in restricted functional area, especially when furniture is arranged improperly,
- Poor access to hanging cabinets in functional areas outside the reach of a disabled person requiring the lowering of their position or regulation of their height,
- Lack of recesses for the legs of a wheelchair user under cabinet worktops and sink requiring special adaptation [1, 9].

The study presents two contemporary design solutions: design adaptation of a kitchen for the requirements of a wheelchair user (Fig. 1) and a design of a new, open kitchen with a 'technological isle' with no barriers for disabled users (Fig. 2).

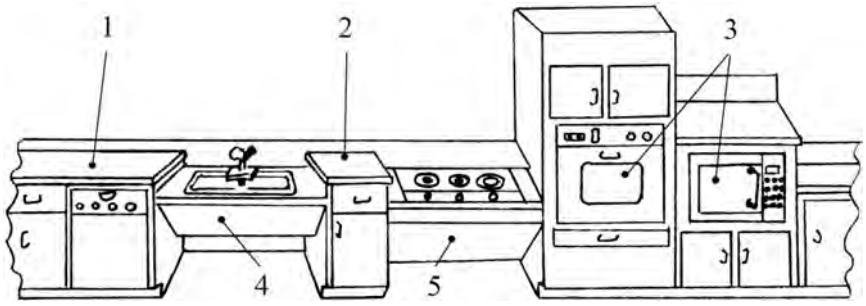

Fig. 1. An example of kitchen adaptation with row arrangement for the needs of disabled users of wheelchairs: 1 – dishwasher of standard height or raised 15 cm; 2 – manoeuvring space – min. 30 cm; 3 – cooker and microwave with adjustable positioning; 4 – sink with a recess for knees; 5 – cooktop with a recess for knees (Source: prepared by authors based on [10])

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The most important recommendation is to pursue principles of good work organisation which can be listed as follows: a/ work tool should always be within the arm's reach, b/ places of product storage should be visible and within the user's reach regarding the grip of the product, arm's reach and force of upper limbs, c/ basic functional zones: (1) product storage, (2) product processing and washing up of kitchen utensils and (3) food preparation and their thermal treatment make it necessary to arrange specific arrangement of kitchen equipment and furniture in the above-shown sequence in accordance with the criterion of traffic minimisation during operations. It should also be remembered that there are specific dimensional requirements of individual kitchen furniture and their mutual position which result from accessibility, visibility and user's safety [11].

A synthesis of special furniture solutions ensuring independence of disabled persons is presented in Table 1 in which two types of disabilities resulting from the disability of limbs and vision are compared.

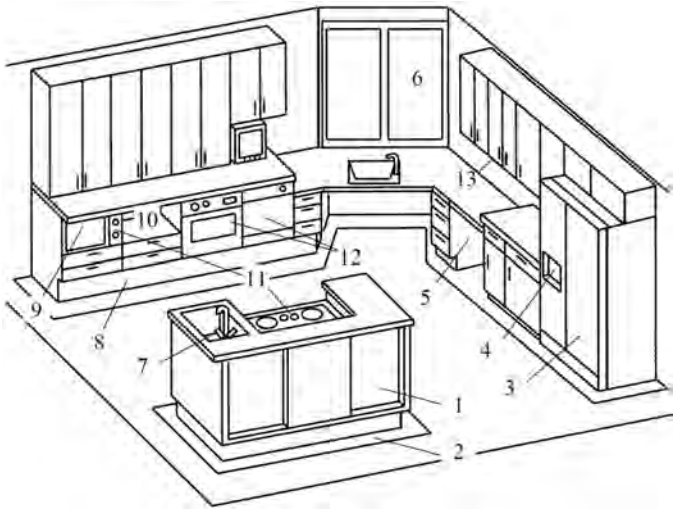

Fig. 2. An example a design of a new, open kitchen with a 'technological isle' with no barriers for disabled users: 1 – sliding door; 2 – contrasting colours of edge; 3 – light doors; 4 – door for water and ice; 5 – open space for legs (wheelchair); 6 – daylight lighting; 7 – convenient kitchen sink; 8 – distinct recess for feet (wheelchair); 9 – front with easy access; 10 – free storage space; 11 – front access controls; 12 – use of regulated mounting; 13 – regulated height of cabinets (Source: prepared by authors based on [12])

Table 1

Contemporary concepts of kitchen solutions for disabled persons

Walking disability	Visual disability
Mobility of height movement and positioning of furniture worktops: (1) hanging cabinets with internal racks lowering or lowering and pulling out ; (2) standing cabinets movable (manually on wheels with brakes or electrically); (3) corner cabinets with rotating baskets; (4) swung tables; (5) telescope rolling guideways for drawers or deep shelves	**Electrical devices**: (1) acoustic signals; (2) well-visible service elements; (3) ceramic heating plates easy to clean
Recommended open kitchen space connected with other rooms aiding integration and comfortable movement: (1) technological isles containing aggregated facilities (heating plate, sink, worktop) with convenient access (no collision); (2) traditional kitchen on a square plane with the L-shaped built-up area; (3) lower built-up area easy to service; (4) traffic areas free of barriers; (5) recessed low edges of cabinets to allow wheelchair access; (6) electrical heating plate (with improved reduced possibility of catching fire); (7) transparent fronts or bottoms to see what is inside	**Furniture:** (1) system of cabinet hanging; (2) external surfaces well filled; (3) rotating fronts which do not use space; (4) optimal internal division
Single-handed utilisation: (1) integrated single-handle faucet with a mixer and shower; (2) handles and rails; (3) guideways, moving elements of small rolling resistance or relieved (4) depth adjustment of worktops; (5) furniture and equipment protected against damage by the wheelchair	**All elements of kitchen equipment:** (1) Safety devices against possibility of injury as a result of collision, (2) well-marked, characteristic traffic routes

Source: (our own elaboration)

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In the case of locomotor disability, the following features were considered as characteristic for increased accessibility: possibility of movement and height positioning of furniture, open kitchen space with a technological isle and single-handed utilisation.

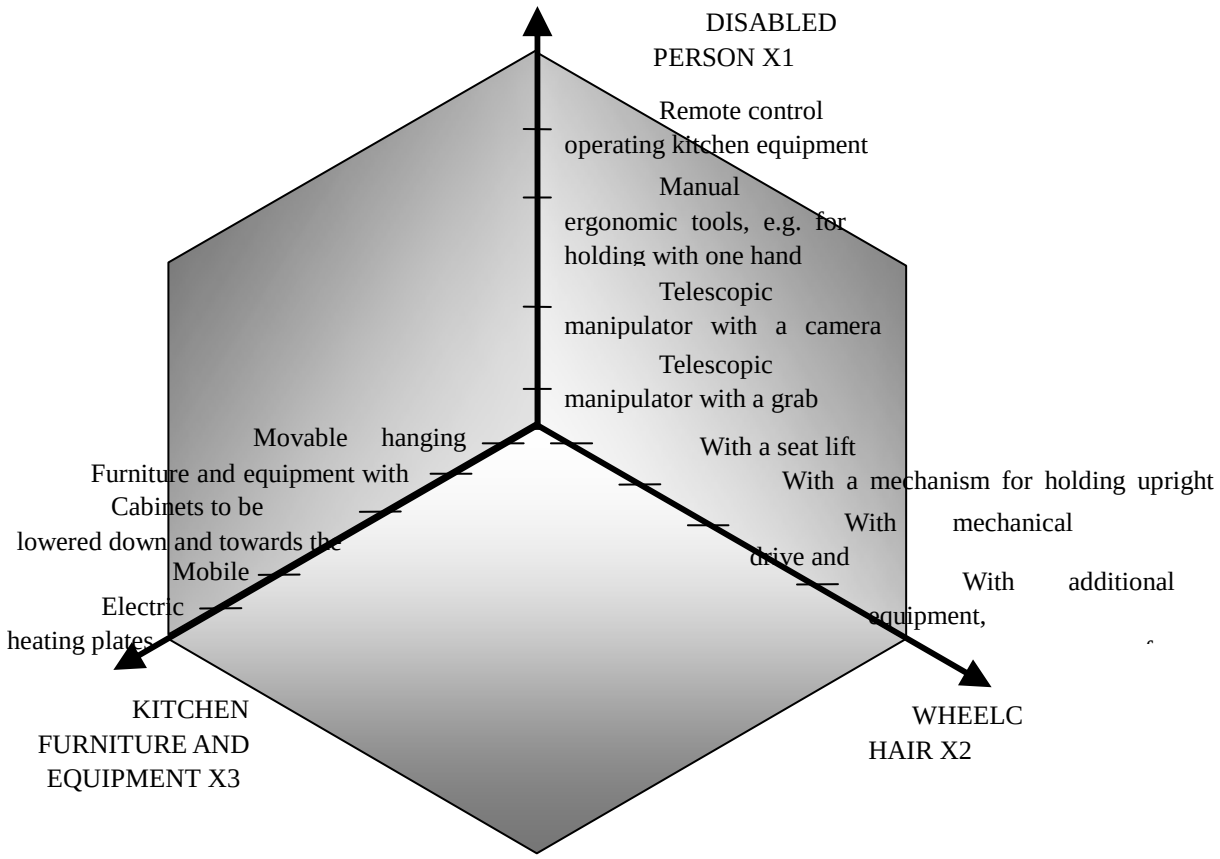

Fig. 3. Morphologic table of adaptation changes in an integrating kitchen
(Source: our own elaboration)

The initial point X1, X2, X3 of (0, 0, 0) coordinates represents the initial situation with the disabled person not equipped in additional tools, with a universal wheelchair and standard kitchen. The area of changes may include individual element changes of the X1, X2, X3 system or a group of changes in one system element, e.g. <x3> or a set of changes in different system elements <X1, X2, X3>.

Increased effectiveness of kitchen furniture for the handicapped with possibilities of movement or swivelling deserves attention (Fig. 4). This trend is supported by a considerable decrease of prices of electrically controlled drives and their operation. In real terms, possibilities of adaptation of the required manipulation space for the arm reach zones have increased for disabled persons moving on wheelchairs. Usually, out of three available adaptation methods in the adaptation system: “disabled person – wheelchair – kitchen equipment”, only one is used, namely adjustment of the person on the wheelchair to kitchen equipment. The remaining possibilities, i.e. lifting the man on the seat lift of the wheelchair or holding the person on the wheelchair in an upright position or, alternatively, artificial lengthening of arms equipped in telescope manipulators [13] are rarely employed.

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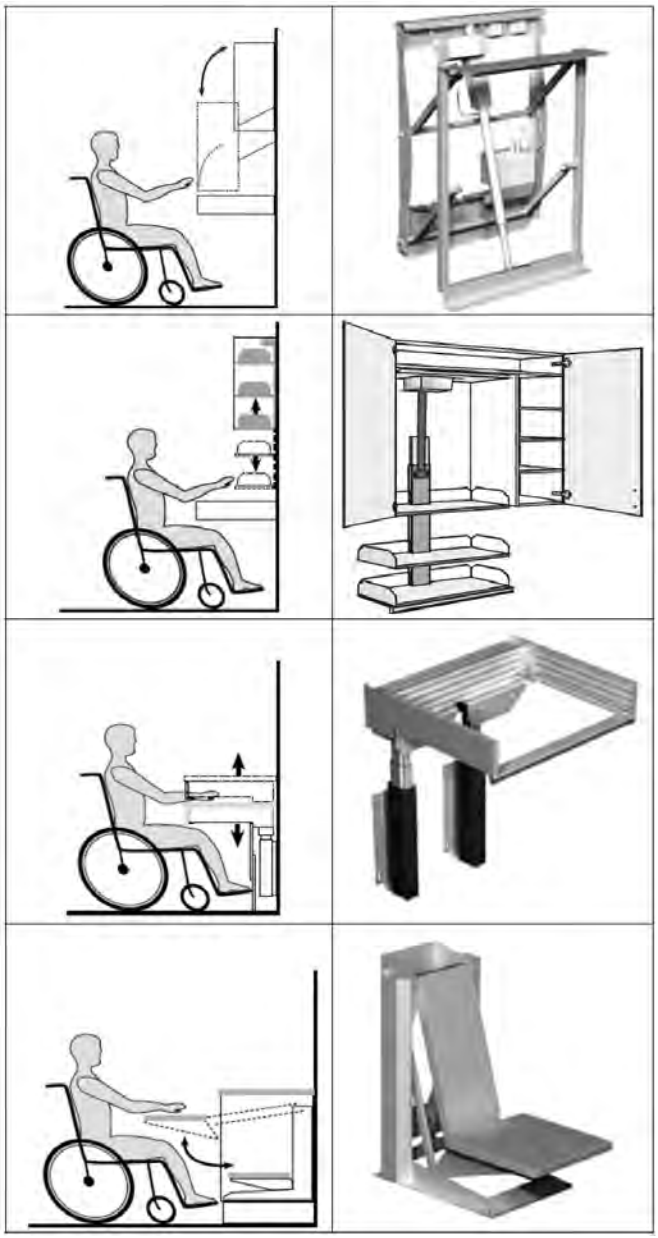

Fig. 4. Mobile kitchen furniture in applications for the disabled and structural principles (Source: prepared by authors based on [14])

Graphic 3D database regarding arm reach and forces of a male person sitting on a wheelchair

Empirical data about reaches and forces of arms were obtained on the basis of investigations of a paraplegic sitting on an active wheelchair. The experimental station for static and dynamic reaches of arms (Fig. 5a) consists of a circular plate of a measuring protractor I in the axis of which in the reference point SRP of a person 3, a wheelchair 2 was placed (height y_0=55 cm).

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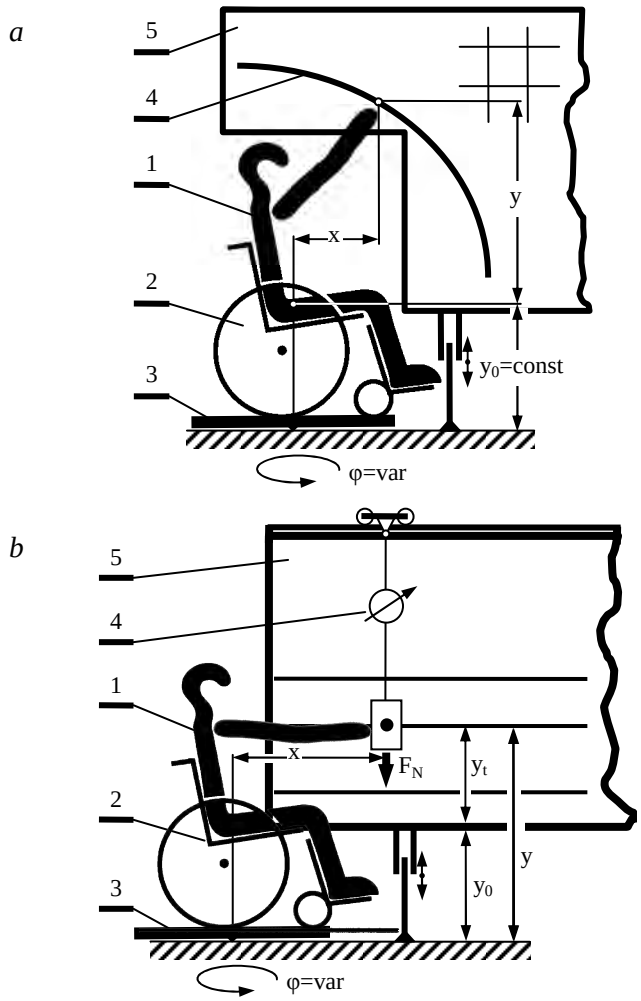

Fig. 5. Block diagram of a measurement stand and method of arm reaches (a) and arm forces (b) of a disabled person sitting on a wheelchair in a 3D space of geometrical dimensions x, y, φ: (1) – handicapped person; (2) – active wheelchair; (3) – measuring protractor, (4) – reach curve (a) or measuring dynamometer (b); (5) – table (Source: our own elaboration)

The protractor with the wheelchair (or a car seat) and a sitting man can turn in relation to the stationary vertical table 5. The table plane passes through the reference point SRP. In each position of the angle of rotation φ within the range $0 \leq \Delta\varphi \leq 120°$, every $\Delta\varphi = 15°$, static and dynamic curves of the arm reach were plotted. Biomechanical studies of the man's forces were conducted on the assumption of the vertical direction downwards of the force action. The method of the investigations of forces is presented in Fig. 5b. The seat arrangement and position of the table in relation to the seat are identical as in the zone measurements of the arm reaches. The table positioning mechanism at a specific height guarantees possibilities of taking force measurements at three preset levels y: the head (eyes y = 67 cm), shoulders (y = 42 cm) and waist (waist y = 13 cm) of the disabled person against the SRP point. Forces were measured at the following distances: x from 40 to 80 cm; Δx = 10 cm in relation to the reference point SRP. Results of measurements of arms' reaches in the (x, y, φ) system and of arms' forces in the f(x, y, φ) system were converted both numerically and graphically. Numerical data x,y,φ obtained from our own measurements was archived electronically and was used to plot curves of arm reaches in measurement planes at set heights of axis Z. Individual diagrams of arm reaches were then represented by a spline type curve and a Non-Uniform Rational B-Spline (NURBS) surface was spread on the set of curves. In the analysis of forces, the numerical data $F_N = f(x,y,\varphi)$ obtained from transformations were archived in an electronic form. In this way, a biomechanical-anthropometric model was developed of a contour type structure describing free surfaces of a layer with F_N = const. taking advantage of heterogenous B-spline rational functions. NURBS curves are characterised only by restrictions of changes affecting weight values to the nearest environmental point, which differs them from other approximating or interpolating curves. Following the above treatments, the surfaces are represented by a grit of longitudinal and transverse lines improved by rendering.

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Figure 6 presents visualisation of the NURBS surfaces in the course of determination of the static reach zone and zones of forces. The external layer represents the reach and the internal layers represent force zones of the right arm of the examined disabled person. In this way, it was possible to obtain common geometrical 3D anthropometric characteristics of arms' reaches and biomechanical characteristics of the arm's force of the examined object.

The planes of force zones shown in Fig. 6 represent limiting states of forces exerted by the examined subject. There are several different methods of transformation of limiting forces resulting from F_g measurements to allowable F_d forces safe in definite conditions of work. They are brought to the reduction of the limiting force value F_g by the introduction of the product of impact coefficients:

$$F_d = F_g \cdot \prod_{i=1}^{i=n} k_i = F_g \cdot k$$

where: the product of impact coefficients

$$k = \prod_{i=1}^{i=n} k_i = k_1 \cdot k_2 \cdot k_3 \leq 1$$

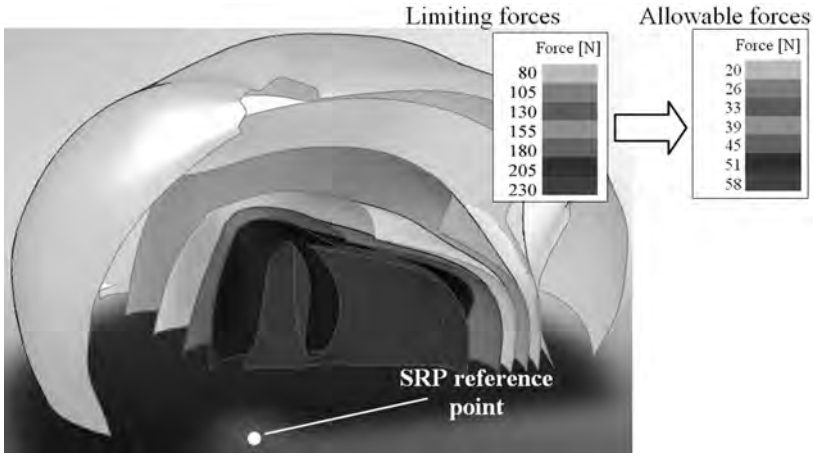

Fig. 6. Set of surfaces determining zones of occurrence of constant forces of the right arm against the external surface of the arms' reach (Source: our own elaboration)

Impact coefficients take into account most commonly: age and gender (k_1), training (k_2) and kind of loading (k_3) and, in this way, it is possible to re-scale values of forces determining force zones (Fig. 6). The above presented method of elaboration of graphic 3D of anthropometric and biomechanical database [2, 15] will be used in future studies.

Investigations on the accessibility and field of vision of a disabled person sitting on a wheelchair in kitchen virtual environment

Accessibility and field of vision for a handicapped person to a cooker or a heating plate in a standard and adapted kitchen

A standard kitchen usually does not fulfil the expectation and requirements of a disabled user. Interactions between the spatial structure of the work station and the user of the kitchen sitting on the wheelchair prevent him/her to adopt typical ergonomic positions. The sitting position on the wheelchair and lack of recesses in furniture as free space for feet makes close approach of the wheelchair to the front of furniture and equipment impossible and prevents the user from adopting a position identical with the standing position of other kitchen users. The sideways approach to furniture and equipment enforces an unnatural position of single-handed work, usually at the limit of arm reach with respect to dynamic leaning. In this dynamic position, work is less comfortable and the body position less stable due to the lack

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of the back support at the height of loins. It is true that at the wheelchair sideways approach to furniture (Fig. 7-Ia), manipulation possibilities increase but, practically speaking, all manipulations must be performed with one hand – right or left – depending on the direction of the vehicle in relation to furniture (Fig. 7-Ib, Ic). Another significant limitation is connected with the arms' reach since only the front part of the heating plate remains within the working range of arms. In addition, considerable distance from furniture causes that work is carried out with arms almost straight, limiting the applied force of the user and easily leading to rapid static fatigue. It should also be remembered that all work is performed sideways and, inevitably, when carried out long, is extremely exhausting.

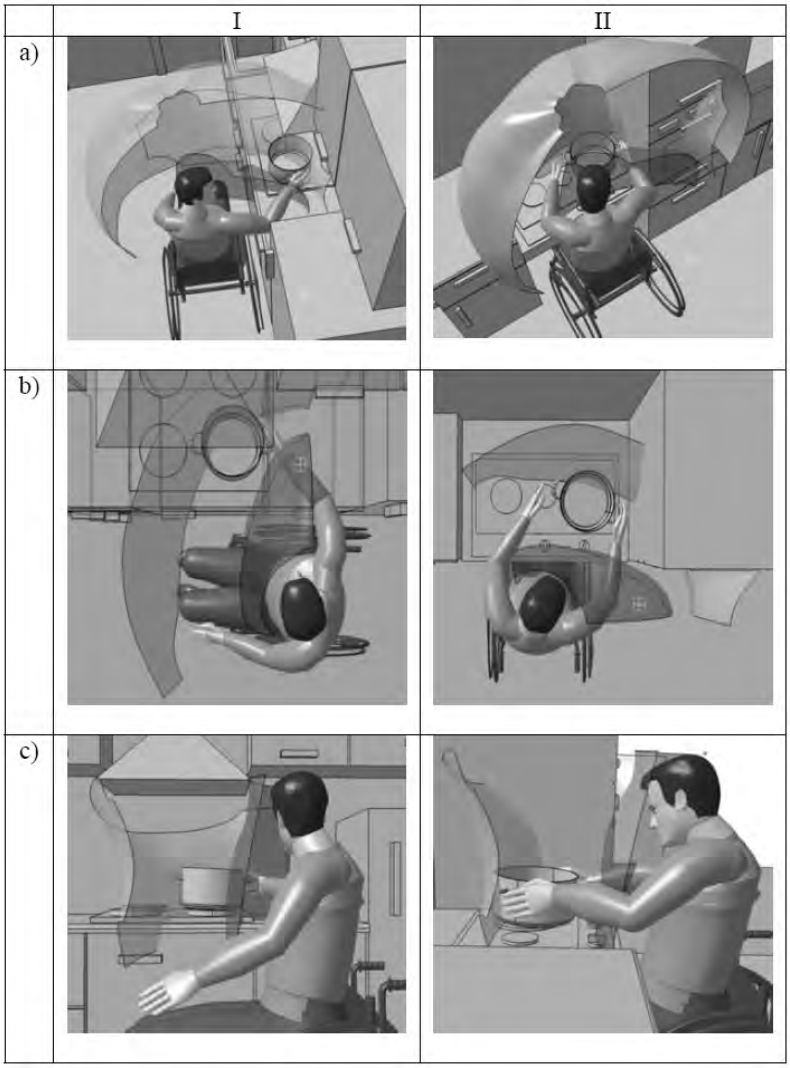

Fig. 7. Visualisation of the reach zone of the right arm and force range during manipulation at the gas cooker in a standard (I) and adapted (II) kitchen; red colour – 180 N zone, beige colour – 80 N zone, grey colour – maximum range of arm reach (Source: our own elaboration)

In an adapted kitchen, the most important technical facilities of the kitchen equipment (e.g. gas cooker, sink) are characterised by appropriately changed dimensions. The height of the heating plate is lowered to suit the figure of the user sitting on the wheelchair. In addition, the removal of the lower part of the cupboard allows sufficient space for legs making it possible for the disabled person to access the device comfortably (Fig. 7-IIa). This position allows manipulation of kitchen utensils with both hands in the frontal half-sphere of the arms' reach. This affords significantly better manipulation possibilities at considerably reduced required muscle forces.

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The field of vision of the workplace in an adapted kitchen is better. The lowered heating plate creates better manoeuvring possibilities with kitchenware and, additionally, affords significantly better observation of the working area as well as the content of individual utensils. The field of vision of the disabled in a standard kitchen is nearly parallel to worktops and, consequently, the entire work field is seen from the side (Fig. 8-Ia). In the case of the kitchen with adapted furniture, the field of vision is moved higher and therefore the user looks at the objects from above (Fig. 8-IIa).

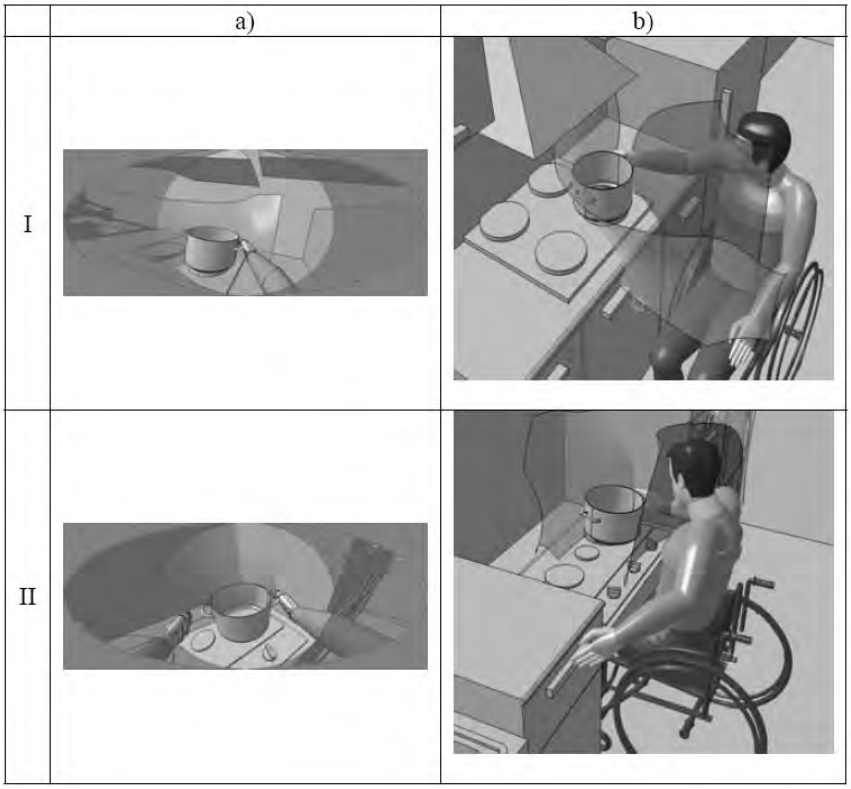

Fig. 8. Visualisation: a) of the field of vision of a disabled person during manipulations at the gas cooker and b) manipulations possibilities of the right arm for a standard (I) and adapted (II) kitchen
(Source: our own elaboration)

When analysing arms' reaches, it is also important to pay attention to possibilities of manipulation with the other (in this case, right) hand. In the case of sideways work in relation to kitchen furniture (Fig. 6-Ib), it is possible to use only one hand when operating equipment for thermal treatment as manoeuvres with the wheelchair are very difficult. In the case of the adapted kitchen, with the possibility of access to furniture from the front, the user can employ the free hand, at any moment, to move around or reach for required elements.

Accessibility and field of vision for a disabled person of hanging cabinets in a standard and adapted kitchen

Among important manipulation activities performed in the kitchen are activities associated with putting in and taking out of kitchenware from cabinets. In the case of a standard kitchen, upper cabinets are situated too high as well as too far due to the lack of recess for legs (Fig. 9-Ia). All manipulations are carried out exclusively with one hand with maximal range of forces (Fig. 9-Ib, Ic). The situation is worsened by the fact that only a certain fragment of the lower shelf of the upper cabinet remains within the maximal reach of the arm. Therefore, the disabled person cannot fully utilise the storage space of the cabinet and is also unable to reach products from further inside the cabinet.

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In the case of the adapted kitchen, application of lower cabinets affords, practically speaking, an unobstructed access to lower parts of the cabinet and somewhat restricted access to upper shelves (Fig. 9-IIa). The objects from the cabinet are taken out with both arms (Fig. 9-IIb, IIc), in the frontal half-sphere, at the full range of reach of both arms. That is why the required forces are significantly lower and the disabled can work comfortably in this kitchen much longer.

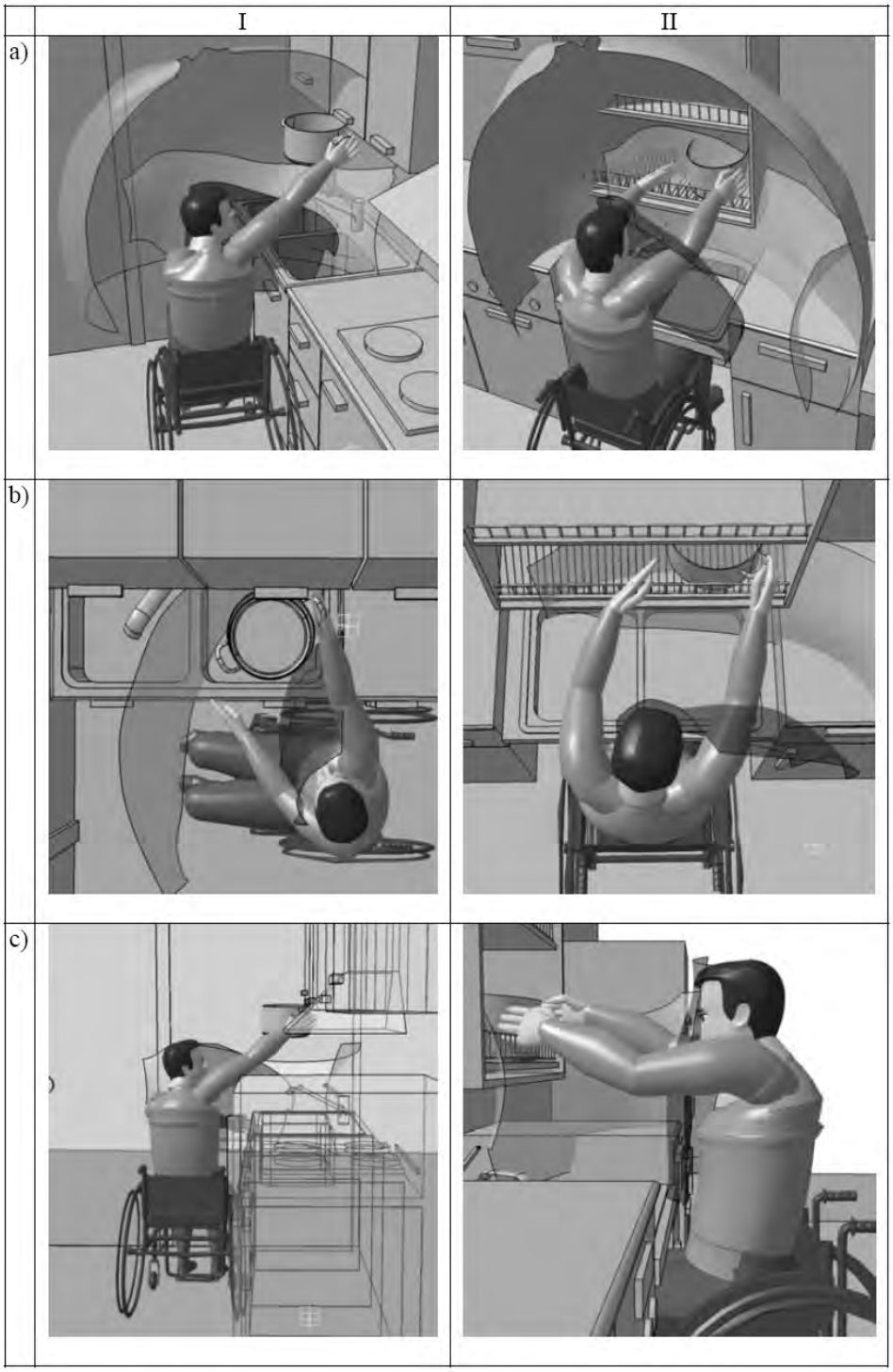

Fig. 9. Visualisation of the area of reach of the right hand and the force range during manipulations at the upper cabinet for a standard (I) and adapted (II) kitchen; red colour – 180 N zone, beige colour – 80 N zone, grey colour – maximum range of arm reach
Source: (our own elaboration)

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The adjustment of the height of cabinets to the handicapped person is also very important from the point of view of the field of vision of the person sitting on the wheelchair. In the case of a standard kitchen, the disabled person must look upwards to see the manipulations field (Fig. 7-I). The lower part of the shelf on which the object is to be put away is totally hidden. In the case of objects filled with liquids, this poses a serious risk of the content being poured out onto the user. Additionally, considerable angles of the raised arms exert a negative influence both on the comfort and precision of performed movements.

In the case of an adapted kitchen (Fig. 10-II), the possibility of lowering the cabinet makes it possible for the disabled to put objects comfortably away on the lower shelf. The point of vision is situated, practically, on the same level as the shelf on which the object is placed. Therefore, the disabled person sees what is actually on the shelf and can avoid collision with other objects on the shelf. This reduces the danger of pouring or spilling out of products onto the user and, at the same time, improves the comfort of work in the kitchen.

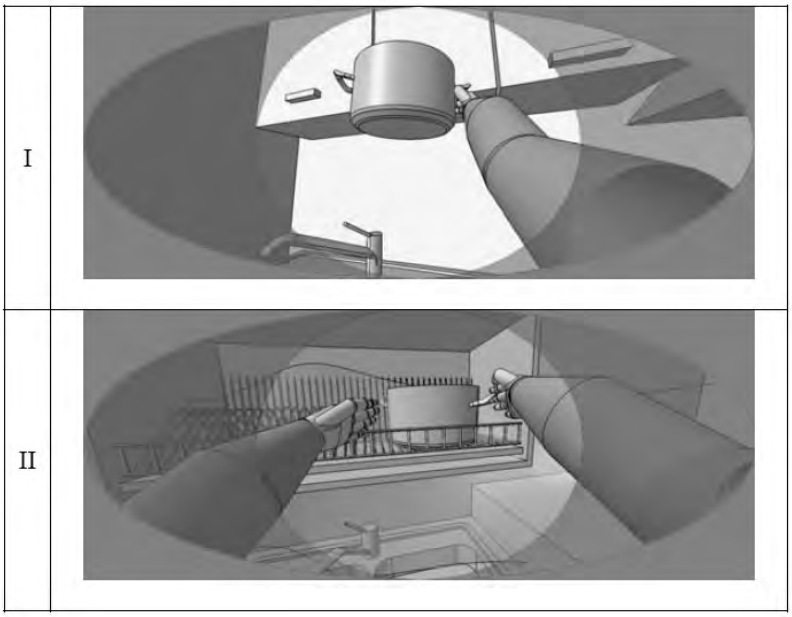

Fig. 10. Visualisation of the field of vision of a disabled person during manipulations at the kitchen cupboard for a standard (I) and adapted (II) kitchen (Source: our own elaboration)

Recapitulation and conclusions

Movement difficulties that the disabled person faces in the kitchen can be divided into two groups. Kitchen facilities frequently are outside the range of arms' reach and/or outside the field of vision which results is lack of access to upper cabinets, obstruction in the utilisation of kitchen facilities, threats of pouring or spilling out of food articles as well as danger of damage of furniture by the wheelchair. Heavy and/or hot objects cannot be transported for distances exceeding effective reaches of arms due to: lack of possibility of access close to kitchen cupboards and cabinets (lack of recess for feet), absence of intermediate surfaces allowing transported objects to be put away for a moment, shifting the wheelchair and continue the transporting and, last but not least, mistakes in designing.

The most important trait of an ergonomic kitchen, from the point of view of a person moving about in a wheelchair, is the appropriate arrangement of furniture and other facilities (access from the level of a wheelchair, appropriate manoeuvring space, elimination of the necessity to transfer objects). The second most important character is the application of technical devices dedicated to individual requirements of a disabled person (equipped in positioning drives, adapted to single-handed operation, resistant to mechanical damage).

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The proposed graphic database allows researchers to carry out digital simulations of various systems of technical facilities making it possible to arrange properly kitchen space in a way that will also take into consideration unrealised needs of users.

A kitchen adapted to needs and requirements of a person moving on a wheelchair should also be ergonomic for able-bodied persons.

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