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Simulation-based time evaluation of basic manual assembly tasks

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ABSTRACT

The paper presents a simple simulation model of the lifting procedure that can be used to predict the total time required for the sequence of basic manual assembly tasks depending on the various parameters of the load and with regard to the workers' health. The aim of the research is to determine the appropriateness of using simulation tool for (re)setting time standards for manual assembly tasks. An avatar in the simulation model performs sequences of tasks with a handling mass of up to 20.5 kg. The individual times obtained from the simulation model were analysed and compared with several time prediction methods and validated in laboratory environment. An analysis of the influence of different load parameters on the total time was also performed. Dependency is mostly linear, so from the practitioner point of view, we can predict with reasonable certainty the total time for any sequence of manual assembly tasks for every size and mass of the box. Based on the results we can confirm that simulation tool JACK is suitable not only for ergonomic analyses but also for setting time standards for the workers. Furthermore, with the simulation tool we analyse the process and get the accurate results in shorter time compared to other mentioned methods.

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1. Introduction

Many tasks at industrial assembly workplaces still require manual work that includes a variety of activities such as loading and unloading, pushing and pulling, and carrying tasks that require manual handling of goods and materials (MMH) [1, 2]. When designing jobs and products the aggregated information on processes, tools, machines, subjects of work, tasks and operators must be taken into account, limitations, which are often conflicting, must be met and a design must be generated, which will be acceptable for all parties involved [3]. In order to address workplace design from an ergonomic and health point of view, it is necessary to predict the times required for a worker to complete individual work tasks. These times are important for determining expected productivity, planning staff and material requirements in the workplace, conducting ergonomic assessments, reducing work-related musculoskeletal disorders (WMSDs), etc. [4-7]. They are usually predicted by the use of Predetermined Motion Time Systems (PMTS), such as the Methods Time Measurement (MTM) and the Maynard Operation Sequence Technique (MOST) [8, 9]. Digital Human Models (DHMs) are effective design tools for visualizations, time analyses and ergonomic evaluation of user and workplace interactions in terms of reach, clearance, visibility and comfort. There is a gap between the use of DHM tools for ergonomic assessment of workplaces and the use of DHM tools for advanced time analysis according to different load parameters and avatar poses. To close this gap, there are still challenges to be addressed [7, 10], and our research is focused in this direction.

In this paper we describe step by step a time assessment methodology for basic assembly tasks in a sequence (multitasking, combined tasks) used in an industrial environment. We compare time reports obtained in the conventional way with the MTM method, the simulation tool Siemens JACK 9.0, a laboratory experiment and a new biomechanical time prediction model developed and presented by Harrari *et al*. [8]. In our case study we focused on whether the simulation done in Siemens Jack produces the same results as the MTM method or whether there are parameters (trajectories of hands, banding routine, dimension and mass of the lifting object) that lead to different times in Siemens Jack simulation compared to the MTM method. In addition, the results of the time analysis were also calculated with the new method NTPM developed by Harrari *et al*. [8] and verified by a laboratory experiment. Other research has also been carried out in the field of time and ergonomics analysis and DHM simulations of the lifting procedure, both in the studies of single tasks and as well in combined tasks.

Firstly, in the literature review, we first concentrate on individual tasks of the lifting procedure and analyses that other researchers have dealt with, taking into account different parameters, gender, mass of the load, etc. Secondly, we will discuss studies on combined tasks. We will also review the case studies of DHM simulation and finally focus on the studies that are most relevant to our case.

Padula *et al*. [11] studied the DHM simulation of trunk movement when lifting the load to different heights. The experiment was performed on different population groups (female, male, students, and workers with and without musculoskeletal symptoms). Martinez *et al*. focused on the study of gender differences in upper limb technique during a lifting task of a 6 or 12 kg box from hip to eye level [12]. Other researchers focused on studying the influence of box weight or handling height on the biomechanical exposure of workers [1, 8, 9], while others investigated the correlation between manual handling and injuries [13-16], and some of them focused on the maximum acceptable weight of a lift (MAWL) and lifting frequency [17, 18]. At this point, it must first be emphasized that our case is focused on lifting and lowering tasks, which are only part of the MMH tasks, and that we have not concentrated on a part of the MMH that includes, for example, pushing and pulling tasks. Secondly, our study is based on the combination of the basic tasks of MMH, as we named it as sequence of tasks or lifting procedure. In the area of combined tasks it is necessary to mention the studies for Straker *et al*. [19]. They combined basic manual handling activities such as pulling, lifting, carrying, lowering and pushing and investigated how the risk of such combined tasks could be assessed. The aim of the study was to compare the risks assessed in single manual handling tasks with the risks of combination tasks according to Maximum Acceptable Weights (MAWs). They concluded that the risk assessment of combined manual handling tasks using MAW measures cannot be performed accurately when using the risk assessments of isolated single tasks. In [20] they focused on ratings of discomfort, exertion and heart rate and concluded that combination task discomfort Sum, Rating of Perceived Exertion and heart rate measures were different to measures of the component of single tasks.

Different DHM tools are used to speed up a manual workplace and to use "what-if" scenarios for time and ergonomic analyses. Many researchers have investigated DHM tool in different situations and industrial fields. Several studies have reported on the use of DHMs in the automotive, aerospace and other industries [2, 10, 21]. There is some research that uses DHM tools as safety training methods [7]. There are also reports of disadvantages in the use of DHM software for example when working with the workers with disabilities [22]. The study focuses mainly on working environments where manual work is presented with the aim of creating new classifications of disabilities related to a manufacturing environment. The problem is that the well-known ergonomic software packages of DHM do not include workers with disabilities for theirs ergonomic and time analysis. Other studies, more related to our case study, have focused on work cycle time and time prediction models [6, 8, 9, 23]. In many cases, the PMTS method does not accurately take into account the physiological and biomechanical aspects in time predictions. Especially in cases of lifting, carrying and lowering objects, the PMTS method predicts a shorter time period than a worker is capable of performing without health consequences in the future.

The most relevant studies regarding our research on time prediction models can be found in [8, 9, 24]. The [9] covers the MTM experiment and MOST analysis, but compared to this research it does not include computer simulations. The focus is on the whole body of the worker and the aim was to develop a new time prediction model. The [8] deals with the design of a workplace with manual material handling tasks. It considers both productivity and ergonomics. It includes the DHM simulation tool and proposes a new time prediction model to be used in our study. The same new time prediction model was used in [24], as a parameter for optimization of the productivity. In [24] authors presents an innovative framework for formulating workplace design as an optimization problem that maximizes productivity while maintaining ergonomic assessment values below commonly used thresholds.

Based on the literature review described above, we can conclude that the DHM simulation tool is mainly used as an ergonomic assessment tool, rather than as a tool that can be used in the process of workplace design based on time analysis and different load's parameters. Therefore, the main idea of our research is the usage of the DHM for both, ergonomic and time-based analysis, which can be performed in much shorter time compared to other mentioned approaches and with equal time prediction accuracy, is useful and reliable method.

2. Materials, methods, and experimental work

In this section the methodology, the methods of study and the analysis of our research are presented step by step. The research is divided into two parts, as shown in Fig. 1. The first part is a comparison of the total times obtained with four methods (MTM, Jack tool, NTPM, laboratory experiment) and a second part is a study of the influential parameters. Besides the overview, the methodology is divided into three sub-sections, the first part is a case study presenting the basic assembly operations. The next subsection is a comparison of the methods and an explanation why and how different basic operations can be compared with each other using different methods. The third part deals with the influential parameters of the box.

2.1 Overview of the research approach

The overview of the research approach and the steps of the case study are shown in Fig. 1. The study is divided into two parts. The first part includes a time analysis of the total time of the lifting procedure. The lifting object is the cube-shaped box with evenly distributed weight. The dimension (height/width/depth) of the box is 400 mm and a mass is 13.5 kg. The lifting height is 800 mm. The results of the time analysis were obtained with four different methods (Jack simulation, MTM method, NTPM [8], laboratory experiment). The study is only a simulation study, which aims to test the difference in the results due to the different time prediction models. The results were compared to determine if simulation is a suitable tool for designing work tasks. We know that the simulation tool enables "what-if" scenarios, which only facilitates and speeds up the planning of work tasks, but if the tools were also suitable for design, it would make it easier to set time standards for workers. The simulation was carried out in the Siemens Jack program based on the MTM method. For comparison, we calculated time standards for the sequence of tasks with the classic MTM method and the NTPM method, which extends certain times for the execution of tasks by the worker with the aim of not causing injuries or WMSDs. The results were also verified by a laboratory experiment with 10 healthy students. All subjects were recruited on a voluntary basis.

The total time of lifting procedure TT [s] (manual material handling process) consists of walking, banding, applying force, lifting, carrying (walking with box), putting the box (lowering) and posing in neutral position.

$$TT = t_{walk} + t_{band} + t_{apply} + t_{lift} + t_{carry} + t_{lower} + t_{pose} \quad (1)$$

where t_{walk}, t_{band}, t_{apply}, t_{lift}, t_{carry}, t_{lower}, and t_{pose}, are the times required to walk, to band for the mass (box) reach it and grasp it, to apply force to the mass, to lift the mass, to carry the mass (walking with mass), to lower the mass (put and release the mass) and to pose the body in neutral position.

Individual times has different dependency among parameters. Following equations (Eq. 1 – Eq. 8) show functional dependency for each time, which participate in Eq. 1.

$$t_{walk} = f\{d_{walking}, d_{turning}, v\} \quad (2)$$

where $d_{walking}$ [mm] is distance walk without object, $d_{turning}$ [mm] is distance when turning without object and v [m/s] is velocity of walking/turning. Walking and turning distances are exclusive, so we use $d_{walking}$ for task walk and $d_{turning}$ for task turn the body.

$$t_{band} = f\{\Delta\theta_{TB}, \omega_{rB}, d_R; dim\} \quad (3)$$

where $\Delta\theta_{TB}$ [°] is trunk extension angle, ω_{rB} is angular velocity [s^{-1}] of body, d_R is reach distance [mm] towards the object, and *dim* [mm] is dimension of the box, which is important for grasp operation.

$$t_{apply} = f\{m, dim, \mu\} \quad (4)$$

where m [kg] is weight of the object, *dim* [mm] is dimension of the object and μ is friction coefficient between two materials (skin, cardboard).

$$t_{lift} = f\{m, \Delta\theta_T, \omega_r(m)\} \quad (5)$$

where m [kg] is weight of the object, $\Delta\theta_{TB}$ [°] is trunk extension angle and ω_r is angular velocity [s^{-1}] of body and object weight.

$$t_{carry} = f\{m, d, v\} \quad (6)$$

where m [kg] is weight of the object, d [mm] is distance of carrying (walking with object), and v [m/s] is velocity of walking.

$$t_{lower} = f\{m, \Delta\theta_T, \omega_r(m), pos\} \quad (7)$$

where m [kg] is weight of the object, $\Delta\theta_{TB}$ [°] is trunk extension angle and ω_r is angular velocity [s^{-1}]. "*pos*" is position of the object when releasing it. Position contains class of fit, case of symmetry, ease of handling.

$$t_{pose} = f\{joints\ location\} \quad (8)$$

where "joints locations" means the differences between current joint location and joint location of neutral pose.

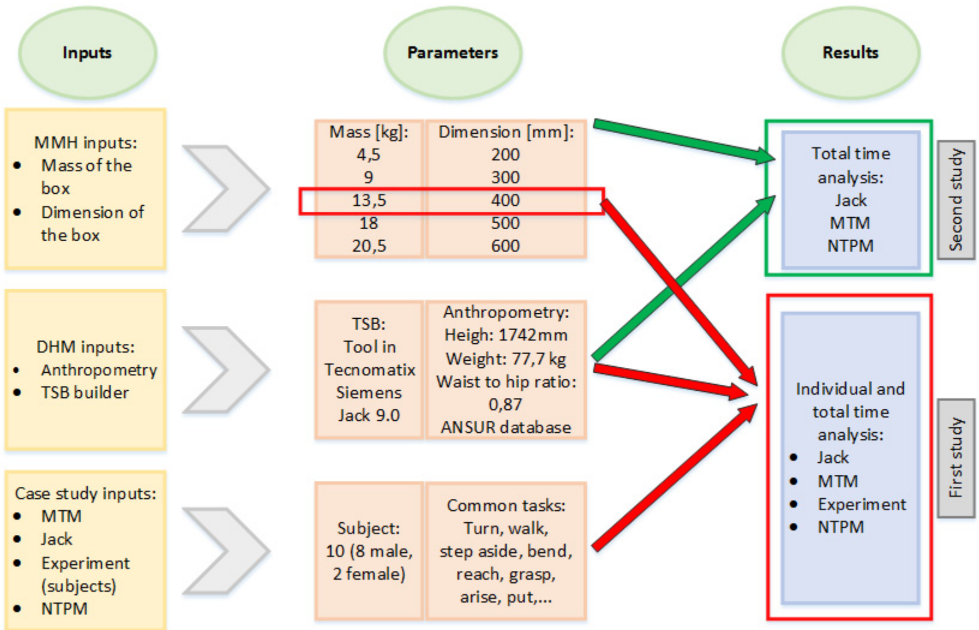


Fig. 1 Overview of the inputs, the parameters and the results

The second part of the study includes the total time analysis with different parameters of the load during the lifting and lowering procedure. The parameters we varied are the dimension (height, width, depth) and the mass of the load (box). The time analysis was performed by simulation in the Jack program, by the conventional MTM method and by the NTPM method. The lifting height is 800 mm. The analysis covers five different dimensions of boxes, i.e. cubes without handles. The dimensions of the cubes (*height* = *width* = *depth*) are 200 mm, 300 mm, 400 mm, 500 mm, 600 mm. The weight of the box is evenly distributed. Mass of the box covers the following values: 4.5 kg, 9 kg, 13.5 kg, 18 kg and 20.5 kg. The comparison was therefore made with 25 different combinations of parameters.

The purpose of the first study on the review of total working time using four methods and tools is to determine whether the simulation tool is suitable for work design and the definition of the relevant standards/norms for workers in industry. This would significantly reduce the time needed to design a workplace and make workplaces more worker-friendly. The purpose of determining the relationship between box dimensions, box weight and time according to the MTM, NTPM and Jack methods is to test whether the simulation tool shortens or lengthens the overall working time when the avatar lifts or lowers a larger or heavier box (Study 2).

2.2 Case study

Our case study is an example of a simple and common problem for the manual assembly process in industry (warehouses, manual assembly area, logistics, etc.). The definition of the problem is a lifting procedure and its time analyses. Most manual assembly process in industry, especially order-picking systems used in practice, are manual "picker to part" systems, and more than 80 % of all orders processed by warehouses are picked manually [25]. The order picking process, a process in which humans are routed by picking lists to items' storage locations to retrieve items for customers, is the most laborious and the most costly activity (up to 55 % of cost of the process [26]) in a typical manual assembly process. Since walking presents up to 50 % of the total time and lifting is most ergonomically stressful the logical way of improving lifting procedure (walking, turning, lifting, carrying, etc.) is to study time spent on procedure and try to reduce it by detailed research like we proposed. The problem definition of lifting procedure, which contains walking, turning, banding, applying force, lifting, carrying, lowering and posing is to determine if simulation tool is appropriate tool to assess time of the procedure. The object of study is lifting procedure of a box with a mass of m = 13.5 kg and dimensions of $A \times B \times C$ = 400 × 400 × 400 mm (*height × width × depth*) from the floor to the table. In the initial state, the worker stands in front of the table, facing the table, and the box stands on the worker's left. The main task of the worker is to move towards the box, pick it up and put it on the table. We have separately performed the calculations for the time analyses with the MTM method, the new proposed time prediction model and the simulation experiments with the software tool JACK. To bring our case study closer to the industrial environment where these activities are common (lifting, carrying, etc.), we set up the laboratory experiment and performed the same sequence of movements. Our case study includes the next sequence of tasks (Fig. 2). First, the worker turns his body by 90° from its initial position. Then the worker starts walking parallel to the edge of the table towards to the box. He walks a distance of 1200 mm (Fig. 2a). The worker takes two lateral steps to achieve a gap between his feet to lift the box more easily. When the worker is in a balanced position, he bends to the box and prepares for the next move, which is reaching for the box (Fig. 2b). The worker picks up the box in the middle of the bottom edge. He grasps it with both hands and applies a force corresponding to the load. The worker lifts the box and regrasps it up again for easier carrying. After that, he straightens his body to the neutral position (Fig. 2c). Then he makes a 180° turn and walks back in a straight line. The distance he walks is 1200 mm (Fig. 2d).

Fig. 2 Tasks from the sequence: a) turn the body by 90° and walk; b) bend the body and reach the box; c) lift the box; d) turn the body by 180° and walk; e) put the box on the table and take a neutral pose for the body

The worker turns his body towards the table. Then he puts the box on the table at a height of h = 800 mm. The position of the box on the table is not important and for this reason we use the "Put" movement command and not the "Position" movement command. The "Put" movement only places the box on the table without defining a tipping point, while the "Position" movement requires a specific point to be defined where the box is to be placed. After putting the box on the table, the worker returns to the neutral pose facing the table (Fig. 2e). The study was also mentioned in an already published paper [27].

MTM method

We calculated the time sequence of basic movements with the MTM method by following the instructions of Karger [28]. For our study we mainly used body, leg, and foot movements, such as sidestep, turn body, bend, arise, and walk. Other basic movements that we used emphasize hand motions, like reach, (re)grasp, apply force, move, and release. Some of these elements are used simultaneously, so we merged them together. For the time analyses of the simultaneous motions only the time for the individual motion is set so that it takes the greatest time [28].

New time prediction method (NTPM)

In our case study we used the NTPM method developed by [8] and calculated new times according to their results. The authors of the proposed NTPM took the MTM model as a basis and updated it for all movements in which the load was included. In our case we take into account the individual times from the MTM methods for the movements: turning, walking, sidestepping, bending, reaching, grasping, application of force and release. For movements where the worker handles the material (box), the exact weight of the box is taken into account, and we have calculated new individual times for the lifting, carrying, turning (carrying) and putting (lowering) movement by Eq. from 9 to 13. In addition to the weight of the box, the improved model also takes into account the angular velocity (ω_r) and the trunk-extension angle (θ_r), which we have taken from the simulation tool.

$$\omega_r(m) = -0.137662 \cdot m + 14.3881 \tag{9}$$

Empirical obtained Eq. 9 presented the correlation between the object mass m [kg], and the average angular velocity ω_r [s^{-1}]. Thereafter, the box lifting time, t_{lift}, was calculated (Eq. 10) using trunk extension angle $\Delta\theta_T$ [°] and the average angular velocity ω_r [s^{-1}].

$$t_{lift} = \frac{\Delta\theta_T}{\omega_r(m)} \tag{10}$$

Empirical obtained Eq. 11 presented the correlation between the object mass m [kg], and velocity of walking with object (carrying) v [m/s].

$$v = 5.229512605 - 0.09390347244 \cdot m \tag{11}$$

The box carrying time t_{carry} is given by Eq. 12;

$$t_{carry} = \frac{d}{v} \tag{12}$$

where d [mm] is the carrying distance, and v [m/s] is the carrying velocity in Eq. 11.

Average time for box lowering is 13 % less than that lifting under the same conditions. Thus, using the change in trunk angle $\Delta\theta_T$ [°] and angular velocity for lowering ω_r [s^{-1}], the lowering time t_{lower} was calculated as Eq. 13:

$$t_{lower} = \frac{\Delta\theta_T}{1.13 \cdot \omega_r(m)} \tag{13}$$

Simulation tool Jack

We programmed the same lifting procedure in the software tool JACK with the use of the TSB (Task Simulation Builder) tool in a virtual environment. The TSB tool automatically generates the timeline for each movement separately. We used eight different movements (go, pose, get, apply force, reach, regrasp, position, put), some of which (e.g., go) were repeated several times. Even though Jack (TSB) uses the MTM method as a basis, it makes sense to make a time comparison between TBS and MTM results, because in a virtual environment we place an avatar in different postures, which leads to a change in duration for each task.

Although the names of the individual movements differ in the MTM method and in the simulation experiment, their meaning is the same, so we can compare them. For example, it can be stated that the movement "go" in the simulation tool is used to walk, carry and turn the body, and the movement "get" is represented by the MTM method as bending and reach.

Practical experiment

In the laboratory environment we set up a system for conducting a practical experiment (Fig. 3). The experiment includes 10 healthy students. Their mean (*SD*) anthropometric data were: age 26 (1.5) years; body mass 75.5 (6.3) kg; height 1760 (55) mm.

All the subjects were recruited on a voluntary basis. All subjects filled in a screening questionnaire to ensure that they were in good health (i.e. that they did not suffer from any of the following: chronic illness, heart condition, musculoskeletal disorders, or injuries). They all signed a consent form approved by the institutional review board of the Faculty of Mechanical Engineering, University of Ljubljana. The experiment was conducted 20 times, two times per student. They performed the following movements: turning and walking from a starting point to the box that is 1200 mm away from the table (Fig. 3a), sidestepping, bending to the box and reaching for it (Fig. 3b), applying a force, lifting the box (Fig. 3c), turning and walking to the table (height 800 mm) (Fig 3d), putting the box on the table and posing in the neutral position (Fig. 3e). All 20 experiments were recorded for further analyses.

a) b) c) d) e)

Fig. 3 Practical experiment: a) turning the body by 90° and walking; b) bending the body and reaching for the box; c) lifting the box; d) turning the body by 180° and walking; e) putting the box on the table and taking a neutral pose of the body

2.3 Comparison of the method

All methods used in our research are based on the MTM methodology, with the exception of the practical experiment, which is an indicator of the actual performance of the subjects. As shown in Table 1, different terms are used for the basic movements in all four methods. We can see that the main difference is only in the naming and the merging of several movements together; the purposes and meanings are the same everywhere, so in summary we can say that the methods are comparable. The results of each method were obtained in different ways: for the MTM classical method, the results were calculated using tables and recommendations [28]. In the Jack simulation environment, a time report is automatically generated based on the avatar, its trajectories, and the parameters you insert in the program. In the NTPM method, the results were obtained by calculation according to the classical MTM method and the addition of taking into account the mass according to Eq. from 9 to 13.

Table 1 Comparison and description of the basic movements for all four methods

MTM method	NTPM	Jack simulation	Practical experiment
Turn body by 90°	Same as MTM	Go (turn)	Turn
Walk	Same as MTM	Go	Walk
Left sidestep	Same as MTM	Pose	Sidestep
Right sidestep	Same as MTM		
Bend	Same as MTM	Get	Bend and reach
Reach	Same as MTM		
Grasp	Same as MTM		
Apply force	Same as MTM	Wait (time from MTM)	Apply force
Arise	Lift	Position (arise and reach)	Lift
Move the box			
Regrasp		Regrasp	
Turn body by 90°	Carry	Go (turn)	Turn by 180°
Turn body by 90°			
Walk	Carry	Go	Walk
Turn body by 90°	Carry	Go (turn)	Turn
Moving the box	Lower	Put	Put
Release the box	Same as MTM		
Neutral pose	Same as MTM	Pose	Neutral pose

2.4 Parameter combination

We performed 25 simulation experiments (5 different masses of the box multiplied by 5 different dimensions of the box) with different combinations of masses and dimensions of the box (parameters in Fig. 1). We compared all versions using the MTM method, the NTPM and JACK the simulation tool, focusing on the total time.

3. Results and discussion

In this section we present the results of the time analyses for the job and task. The section is divided into two parts. The first part shows the results of the time analyses of the individual tasks, which were achieved using all four methods. The second part presents the results of the influential parameters obtained with all three methods: MTM, NTPM, and Jack simulation tool.

3.1 Time analyses of the individual tasks

All movements in all methods were unified so that they are comparable with each other. In the MTM method we combined simultaneous movements so that we obtained a total of 11 movements which are the same in all four methods we compared. The movements and the corresponding times are shown in Table 2. The box we used in this part of the study has a dimension of 400 mm and weighs 13.5 kg.

Table 2 Comparison of the individual times of the basis movement for all four methods

		MTM	NTPD	Jack	Experiment
#	Task description	Time [s]	Time [s]	Time [s]	Time [s]
1	Turn body by 90°	0.67	0.67	0.2	0.97
2	Walk	0.76	0.76	1.34	1.97
3	Sidestep	0.64	0.64	0.64	0.78
4	Bend, reach and grasp the box	1.30	1.30	2.54	1.02
5	Apply force	0.38	0.38	0.38	0.59
6	Lift the box	1.38	3.50	3.16	1.55
7	Turn by 180°	2.01	0.39	0.78	1.47
8	Walk to the table	0.67	1.10	0.95	1.37
9	Turn by 90°	1.34	0.18	0.17	0.61
10	Put the box on the table	0.35	3.10	1.76	1.25
11	Neutral pose of the body	0.52	0.52	0.50	0.87
	Total time TT [s]	10.12	12.54	12.42	12.45

The total time *TT* [s] for each method was calculated by Eq. 1. It can be noticed that the terms of the Eq. 1 and task names are not the same. These are only word differences and not substantive ones. Here are the explanations of meaning for each terms of Eq. 1 according to task description. Task #1 "turn body by 90°", #2 "walk" and #3 "sidestep" contributes time to the first term of Eq. 1"t_{walk}" and has a functional dependence determined by Eq. 2. Task "band, reach and grasp" contributes time t_{band} to the total time and is defined by Eq. 3. Task #5 "apply force" is described by term t_{apply} and Eq. 4. Task #5 "lift the box" contributes to total time the time t_{lift} and it functionality is described by Eq. 5. Task numbered from 7 to 9 means carrying (walking with object) and its contributions are defined by t_{carry} and functional dependencies by Eq. 6. Task #10 "put the box on the table" means to lower the load (object) and is defined by term t_{lower} and Eq. 7. The last task "neutral pose of the body" contributes time to term t_{pose} and is described by Eq. 8.

The values for the times of all movements are not completely consistent when comparing all four methods. It is clear that the different movements contribute different proportions to the total time. Therefore, the same movement has a greater or less strong effect on the total time if we use different methods. We can see that the movements turning the body and walking, which were obtained by the experimental study, contribute a relatively large proportion to the total time compared to the other methods. The experimental study was conducted in a laboratory environment. The subjects were inexperienced and were only instructed to perform the operations at a pace that would not make them feel uncomfortable if the sequence of tasks was repeated over a long period of time. If we exclude these factors, the walking time would be closer to the results of the other methods.

The next comparison refers to the results obtained with the simulation tool Jack and the NTPM. In the NTPM we only focus on the following movements: lift, turn by 180° with object (carry), walk with object (carry), turn by 90° (carry), and put (lower) – task numbers from 6 to 10, because only these movements take into account the weight of the load and are upgraded by the MTM method. We calculated times by equations from 9 to 13 with the following parameters: m = 13.5 kg; $d_{walking}$ = 1200 mm; $d_{turning}$ = 200 mm; and $\Delta\theta_T$ = 43.6°. It can be seen that the values determined with these two methods for the times of the movements "lift", and "put" (lower) are longer than the times determined with the other two methods (MTM and experimental study). The reason for this difference is that both methods (NTPM, Jack tool) take into account the trunk-extension angle, which also increases the value of time and ensures that the worker has enough time to lift and lower the loads in an ergonomically correct way.

The results of the MTM method indicate that the worker spends most of the time on body turns compared to the other methods. Both in the simulation experiment with the Jack tool and in the experimental study (assuming that the test subjects would be trained) less time is needed to turn the body, because in reality we combine rotation and walking into a simultaneous movement for which we need less time.

Jack tool compared to other methods spend least time for task "turn the body". The reason is that Jack doesn't have a separate "Turn" movement, but you have to use a "Go" movement. This movement requires moving the avatar by a certain distance, and not just turning the whole body in the same place. So we used a distance of 200 mm for the turn and a predetermined speed (specified in the simulation tool) and thus obtained the task time. For turning the body you spend more time than for walking, because of the higher complexity of the kinematics of the joints and here is the time difference. The second task, which is at contrary longer in comparison with other method, is "band, reach and grasp" task. There are two reasons for this. First is that it is necessary to place the avatar in a certain distance from object and also to "attach" the hand for "grasp" movement to a certain place, which, however, differs in each simulation and affect the task's time. The repeatability of this task is achieved only through experience and long-term use of simulation tool. The second reason is that the task itself is predefined in the simulation environment so that the avatar leans towards the object with stretched legs, which did not suit us in terms of comparison with other methods. So we subsequently changed the angles of certain joints (knees, hips, and torso) and thus gained time for this task. When changing such a complex task, the simulation tool determine longer time.

The total time for all the tasks obtained with the MTM method is t = 10.12 s; using the Jack simulation tool it is t = 12.42 s; for the practical experiment it is t = 12.45 s; and the total time obtained with the NTPM method is t = 12.54 s.

In summary, we can say that all methods, except MTM, give almost the same result for the total job time and that we can use any method to design a new job with a sequence of basic movements. In many cases PMTS (the MTM method) predicts a shorter time than the worker is able to work without injury after some time. In such a case, this statement proves to be correct in comparison with the other methods, as the MTM method predicts 20 % less time to perform the same sequence of movements.

In industry it is necessary to plan and design work processes and sequences of jobs as quickly as possible, but it is also necessary to adapt the tasks to the workers and to think about their well-being. With the Jack simulation tool, it is easy and quick to check the ergonomics and suitability of the jobs for workers using "what if" scenarios. This option allows us to modify the various parameters of the simulated objects (weight, dimension, shape) and avatars (gender, anthropometric characteristics). From this part of our study we can conclude that the Jack simulation tool is a suitable method for designing jobs and workplaces when only the total time and not the individual times are of interest. If we want to optimize the work cycle for the study we are discussing, it is necessary to look deeper into the individual tasks and find the relationships between the values of the individual times and the individual tasks, and determine which characteristics (e.g. steps, turning procedure, bending procedure, trunk angles, etc.) have the greatest influence on a particular method.

3.2 Influential parameters

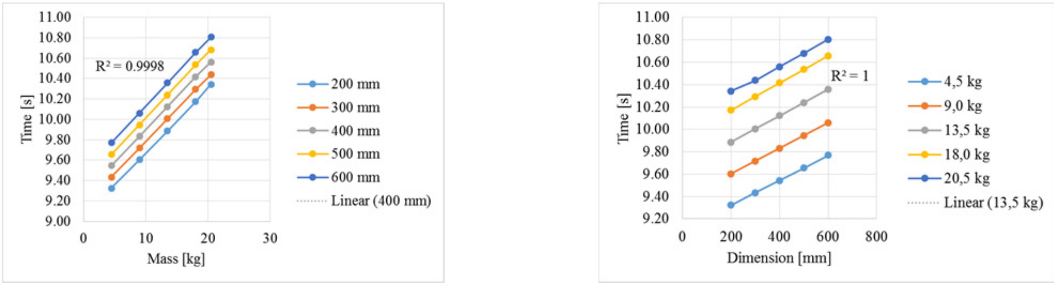
Tables 3 to 5 show the results by MTM, NTPM and Jack simulation. The aim of the influential parameter study was to determine how the individual method takes into account the weight parameter and the load size parameter during the lifting procedure. The results show the total times of the entire sequence of all tasks. The load that appeared in the study is a cubic box without handles. The mass of the box varies from 4.5 kg to 20.5 kg. The dimensions (height = width = depth) of the box vary from 200 mm to 600 mm. Therefore, the study presents 25 combinations of mass and dimensional parameters.

MTM method

When using the MTM method, the mass and dimensions of the box are taken into account when calculating the total time (Table 3). The total time of the tasks and the mass of the box are linearly dependent (R^2 = 0.9998; Fig. 4a). The same applies to the dimensions (R^2 = 1; Fig. 4b). Therefore, if we use the MTM method, we can predict with reasonable certainty the total time for this sequence of tasks for each size and mass of the box. The problem with prediction is that these times are often too short, which means that a worker is not able to perform all movements without further discomfort.

Table 3 MTM: total time analysis for different dimensions and masses of the box

		Mass of the box [kg]					
		4.5	9.0	13.5	18.0	20.5	
Dimension of the box [mm]	200	9.32	9.60	9.89	10.17	10.34	Time [s]
	300	9.43	9.72	10.01	10.29	10.44	
	400	9.54	9.83	10.12	10.42	10.56	
	500	9.66	9.95	10.24	10.54	10.68	
	600	9.77	10.06	10.36	10.66	10.80	



a) b)

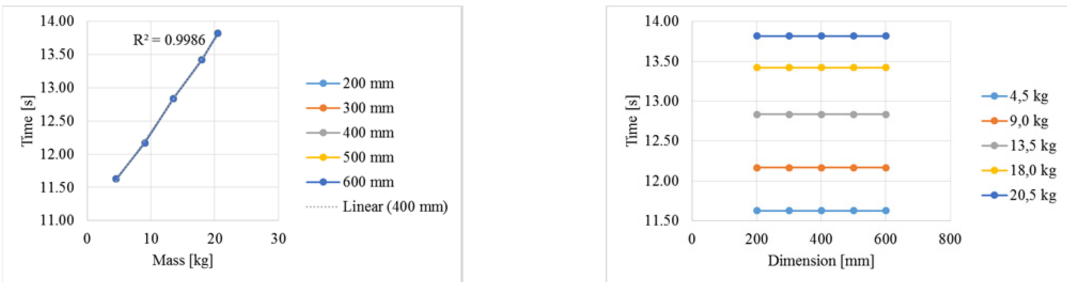
Fig. 4 Relationship between the total time and the parameters: a) mass, and b) dimension using the MTM method

NTPM method

Table 4 shows the values of the total times obtained using the NTPM method. It can be seen immediately that the dimensions of the box are not included (Fig. 5b). The relationship between the weight and the total time is linear (R^2 = 0.9977, Fig. 5a), so for this sequence of movements we can predict the value of the total time for each mass of the box. To calculate the results according to this method we use several parameters (angular velocity, trunk-extension angle) and the mass of the box are used, which gives more realistic total times compared to the MTM method.

Table 4 NTPM: total time analyses for different dimensions and masses of the box

		Mass of the box [kg]					
		4.5	9.0	13.5	18.0	20.5	
Dimension of the box [mm]	Not included	11.34	11.88	12.54	13.13	13.53	Time [s]
		11.34	11.88	12.54	13.13	13.53	
		11.34	11.88	12.54	13.13	13.53	
		11.34	11.88	12.54	13.13	13.53	
		11.34	11.88	12.54	13.13	13.53	



a) b)

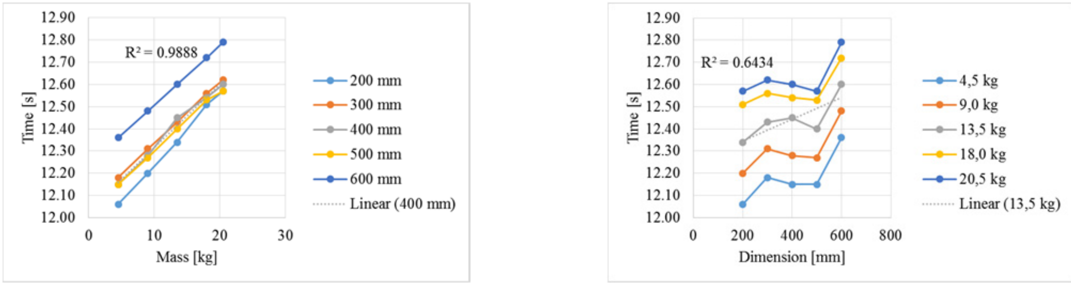
Fig. 5 Relationship between the total time and the parameters using the NTPM: a) mass, and b) dimension

Jack simulation tool

The results in Table 5 show that the time changes minimally when the mass of the load changes. Therefore, the mass of the box has minimal effect on the value of total time, which is not logical or empirical, as shown in Fig. 6a – relationship between total time and the mass parameter.

Table 5 Jack simulation tool: total time analysis for different dimensions and masses of the box

		Mass of the box [kg]					
		4.5	9.0	13.5	18.0	20.5	
Dimension of the box [mm]	200	12.06	12.20	12.34	12.51	12.57	Time [s]
	300	12.18	12.31	12.43	12.56	12.62	
	400	12.15	12.28	12.42	12.54	12.60	
	500	12.15	12.27	12.40	12.53	12.57	
	600	12.36	12.48	12.60	12.72	12.79	



a) b)

Fig. 6 Relationship between the total time and the parameters using the Jack simulation tool: a) mass, and b) dimension

From the results of the analysis of the dimensions of the box it is clear that the dimensions affect the lengthening/shortening of the total time. The change of the duration of a task happens because it is necessary to adjust all positions of the body and joints separately for each task in order to handle the different sizes of the boxes. The total time varies because we cannot adjust the joints in exactly the same way, which is similar to the situation in reality (Fig. 6b).

We can conclude that the results of the simulation show that the mass of the box has a limited effect on the total time. However, a more detailed analysis shows that the change in mass strongly affects the ergonomic analysis of the program package (Lower-Back Analysis – Fig. 7, Manual Handling Limits, Metabolic Energy Expenditure, NIOSH Lifting Analysis etc.). The result on Fig. 7 shows force (L4/L5 force) affecting the lumbar vertebrae 4 and 5. If we want to obtain a "correct" correlation between the mass and the value of the total time in a simulation tool, we should try to place the avatar in different positions and, based on the ergonomic results, extend/shorten the time of each task and consequently obtain more regular values for the total times.

a) b)

Fig. 7 Lower-back analysis – Results for L4/L5 forces [N] based on different masses of the box: a) 4.5 kg, and b) 20.5 kg

4. Conclusion

The simulation model of the lifting procedure is developed for prediction of the total time required for basic manual assembly tasks with different load parameters. The results of the simulation model were compared with different time prediction methods (MTM, NTPM) and verified by laboratory experiment. Workers in manual assembly suffer from rigorous time standards. With the implementation of a simulation model, the time standards of the task can be efficiently redefined to make it worker-friendly.

Our research can be divided into two parts. The first part concerned the individual times and the total times determined with four methods, two of which are time prediction methods (MTM, NTPM), another one is simulation of the worker obtained by Siemens Jack simulation tool, and the last one is a laboratory experiment. The research was carried out on basic manual tasks, which cover only a part of the MMH tasks. The main objective was to determine whether the simulation tool is suitable not only for ergonomic analyses but also for setting time standards for the workers. The literature shows that workers under traditional standards do not have enough time to perform basic tasks, resulting in work-related musculoskeletal disorders and injuries. As we found out in the case study, the basis is the classical MTM method, which gives the shortest total time of the lifting sequence. The NTPM upgrades the MTM method by extending the times due to the load consideration, which results in the worker having more time to recover. The simulation tool, which is also based on the MTM method, leads to differences in the total time value in comparison to the MTM method. The reason is that the TBS tool also takes into account the trajectories of the body, arms, legs, and the way the avatar grasp the load and adds addition-al time on these tasks compared to MTM times. We also verified the sequence of the tasks with an experiment that showed very similar result as the simulation tool. From this we can conclude that simulation is a suitable tool for designing time standards for a sequence of basic methods, although the duration of a single task varies depending on the method used.

The second part of the study focuses on the load of the lifting procedure. We studied the influence of the load on the total time of the lifting procedure. Parameters of the load that were studied in more detail are the mass of the load and the dimensions of the load. As load we used a cube-shaped box with an evenly distributed weight without handles. The case study was performed as a sequence of tasks with 25 different load parameter combinations (5 different box masses x 5 different box dimensions). The case study was performed using three different methods, MTM, NTPM, and the Siemens Jack simulation tool. Depending on the method used, we obtained different results. We found that the MTM method takes both parameters into account but, as reported above, gives too short times for a healthy working practice. The NTPM method only considers the mass of the box, while the dimensions are not considered. The simulation tool, on the other hand, takes the dimensions of the box into account, but the mass of the box has minimal effect on the duration of the tasks, which is in contrast to practice. To overcome this drawback, we have found that the mass has a "correct" effect on the ergonomic result shown by the Lower Back Analysis, so the more detailed study of ergonomics implemented in the simulation tool can lead to a better correlation between the time of execution of each task and the mass of the load.

Further research work will include a determination of this correlation, and how this can be used for an even more realistic estimation of the total time.

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