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Biomechanical Assessment of Lower Limbs Using Support Moment Measure at Walking Worker Assembly Lines

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1. Introduction

Manual assembly line work is currently still necessary in the manufacturing industry. The human body despite its organic limitations is still more flexible than machines, and the human mind possesses creative and intuitive functions above that of robotic devices. Automation and robotic cells have limitations and manual assembly lines are considered a significant and justifiable solution (Hunter, 2002). In traditional assembly lines, such as Fixed Worker Assembly Lines (FWAL), each worker has a designated task, and is required to continuously repeat that task. Although FWALs are efficient and generally reliable, they have the following deficiencies (Wang et al., 2005):

- Low flexibility (in terms of workers and products),
- Need constant attention and management, and
- Difficult balancing.

It is essential that assembly systems are flexible, in order to respond adequately to the changeable characteristics and demands of the market. These demands are typically; an increasing customisation of product, shortening of a product lifecycle, and highly varied production of small batches of product (Miyake, 2006). For this reason, it has become necessary to develop dynamic, flexible and reconfigurable assembly systems. The flexible manpower line (or flexible assembly line), is one of the promising techniques for configuring effective and productive assembly systems, responding well to the challenges of the manufacturing industry (Stockton et al., 2005). It focuses on work force as key resources due to their flexibility and creativity. An example of such systems is so-called Walking Worker Assembly Line (WWAL), in which each worker utilizes various skills and functions by travelling along the manufacturing line to carry out all the required tasks.

2. Description of the WWAL

In last 15 years, several researchers have treated the topic of multifunctional walking (moving) workers performance, in production systems. Wang, Owen and Mileham (Wang et al., 2005) and Nakade and Nishiwaki (Nakade & Nishiwaki, 2008) gave a summary of this

research. In all of this research, application of moving multifunctional workers was found to be limited to a cell in linear or U-shaped production lines. In addition, most of this research referred to the systems under scrutiny by various different names than WWAL.

The term WWAL is recent concept (Wang et al., 2005; Bley et al., 2007). The term is usually used to designate workstations configuration as horizontal “U” shape or straight line layouts. Each multifunctional worker travels by walking down the line carrying out each assembly task at each workstation as scheduled. Thereby, each walking worker completes the assembly of a product in its entirety from start to completion. Figure 1 illustrates concept of WWAL, where a walking worker completes a product assembly process at the last workstation K^* and then moves back to the first workstation 1 to begin the assembly of a new product.

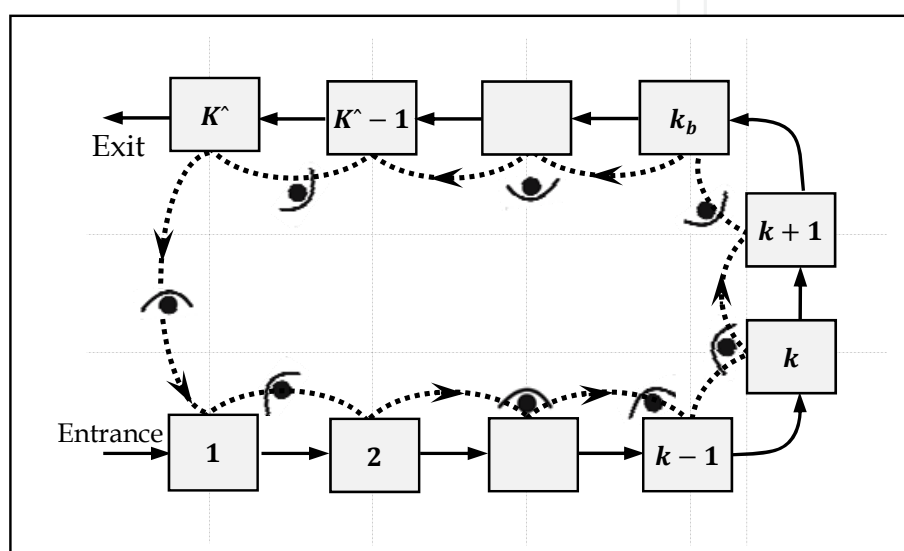


Fig. 1. Form of the walking worker assembly line.

2.1 Workstations and tools

The nature of assembly process at most of workstations in WWAL requires a manual task to be performed by the worker, using simple hand powered equipment such as trimming, riveting and fastening tools...etc. This type of workstation limits worker input to the loading and tooling of components for the end product, prior to the next step in the process. Work-pieces are loaded into a specially designed fixture. The work-pieces then put through a fixed cycle of operations using a predefined range of tools.

The process operations at each workstation are relatively small and highly specific to individual components, utilizing the specialized skills of the worker. The set-up process is relatively quick, thus losing little or no time in non-productive activity, consequently it is more efficient and cost-effective.

2.2 The workers

The workers in WWAL operate to an unaltered, repetitive sequence in which they carry out manual tasks. These tasks consist of the picking up or installing parts, or picking up and using tools and incorporates quality checks or inspections at certain stages of production.

This repetitive sequence is known as a worker operating time. The time taken to complete a worker operating time sequence is known as the overall cycle time. It is the sum of the times required to perform manual tasks, the walking times between the different workstations and in-process waiting time (if exists') of the worker at the bottleneck workstation on the line. Manual transport of components between the workstations of the assembly line requires that the time and energy required doing so, be reduced as far as possible. This is often achieved by shortening the distances between workstations. The WWAL is designed to be able to run effectively with more or fewer workers. The capacity to adjust staffing levels to suite varying required production volumes, is the key to the ability of these lines in response to changes in demand.

2.3 Line layout design

Three types of layout using multifunctional walking (moving) workers have been identified by the authors in terms of the system layout design (Wang et al., 2009):

1. U-shaped design,
2. Straight line design, and
3. L-shaped design.

The U-shaped design is perhaps the most common layout used to implement WWAL. Organizing the WWAL along U-shaped layout eliminates virtually all Work-In-Process (WIP). There are small spaces between workstations to enable a worker with a partially assembled product to queue on reaching the next workstation (if the worker arrives during the time that the preceding worker is still operating at that workstation) until it becomes empty.

Reducing space for in-process waiting enables workstations to be placed very close to one another, thereby reducing the amount of energy and time expended, increasing performance, and efficiently utilizing the available floor space. Close spacing also means products and the rest of the line are more visible to the workers, and is considered to have a beneficial effect on morale. Workers are able to see the progress of parts through the entire line, rather than at just one operation. In addition, shortened travelling distance has other inherent benefits beyond efficiency improvements; not only increased visibility of active areas, but ease of communication and increased teamwork among workers (Grassi et al., 2004; Al-Zuheri et al., 2010a).

2.4 Experiences of manufacturing companies with WWAL

Walking worker assembly line results in a series advantages over a traditional line –FWAL. In this context, rearranging assembly lines from the FWAL to the WWAL by a number of companies has led to achieve the following (Mileham et al., 2000):

1. Increased ease in line balancing, thus reducing the number of buffers required,
2. Flexible and optimal adjustment of the number of line workers to suite output demand, and
3. Minimizing the cost of labour and tooling.

Bischak (Bischak, 1996) and Zavadlav E et al. (Zavadlav et al., 1996) investigated using (moving) walking workers approach in the case of variability in operation times is high (e.g.

manual assembly line). Both found that WWAL gives the best expected production and FWAL is the worst. WWAL system and process design provides workers more control over the speed of the production process and encourages focussed attention to detail, ensuring higher work quality, and hence higher overall product quality. Deploying a WWAL approach also provides increased ergonomic benefits reducing potential muscular-skeletal problems in jobs where single and repetitive tasks are required of static workers. Increased freedom of movement, in particular walking, by the worker in WWAL systems can reduce the probability of Work-Related Muscular-Skeletal Disorders (WMSD), in the arms, back and shoulders (Moller et al., 2004).

Although implementation of WWAL systems offers a variety of benefits to manufacturers (as stated above), it has yet to be widely adopted within the industry. In this regard, Miltenburg (Miltenburg, 2001) stated that U-lines with more than one multi-skilled walking worker rarely run in chase mode, (another name of organising walking workers in this way). Only 1.3% of the U-lines deploying numerous multi-skilled walking workers use this system of production. The Japanese management institute (Gemba Research and Kaizen Institute) interpreted the lack of WWAL deployment in industrial environments to assertions by some practitioners that it has certain aspects detrimental to labour productivity and ergonomic conditions (Miller, 2007). This was mainly due to two main reasons; firstly, adopting WWAL in assembly processes, requires multifunctional workers. These have specialised skills and cost more to employ. Secondly, there is some question as to whether workers actually keep up with completing all required production steps in one cycle time. This claim is based on the time used standing and for carrying in-process products to each process point.

Undoubtedly, the question arises as to whether or not workers will have the endurance to complete a shift time of eight hours, and still have enough energy for a normal life after work. Furthermore, existing research about WWAL or similar dynamic systems (e.g. cellular system) provides only incomplete data modelling for WWAL ergonomics from which to assess the relevant concerns of practitioners about the health and wellbeing of the WWAL work force.

3. Workers postures in WWAL: Implications and investigation

3.1 Workers postures and their implications for workers

Like other manual works in industrial assembly, the tasks of WWAL include lifting, carrying, pushing, pulling of materials, and quality control. Sometimes such work requires frequently lifting heavy loads. This may include the use of non-powered or power hand tools. In addition to that, it may have long cycle and excessive walking time including load carrying (Melin et al., 1999). In general, this work involves postures that cause discomfort and fatigue. These include sustained static neck flexion, shoulder flexion, forearm muscle exertion, extreme wrist postures, and prolonged standing (Lutz et al., 2001).

WWAL is associated with various well recognised health risks resulting from sustained exposure to the above and is a major contributing factor to WRMDs, such as carpal tunnel syndrome, tendonitis, thoracic outlet syndrome, and tension neck syndrome (Lutz et al., 2001). Each of these diagnostic terms is linked to certain types of occupational activity which affect various parts of the body resulting in these painful disorders.

A complete and useful understanding of the performance capabilities of workers on WWAL production lines requires knowledge of the mechanism of musculoskeletal dynamics. Thus, a brief explanation of this is presented in next section.

3.2 Investigation of musculoskeletal dynamics related walking and carrying

Motion such as walking and carrying is achieved by activation of the skeletal muscles (contracting and relaxing rhythmically), to produce the required kinetic energy. The activation of muscles causes bone loading and joint contact forces and consequently allows for moving the joints in a controlled fashion to accomplish the predetermined task requirements (Cappozzo, 1984).

Quite often, motions such as walking and carrying are influenced by a number of inter-individual factors, such as the weight and gender of worker (Brooks et al., 2005) as well as the effect of external forces such as the nature of the job requirements being undertaken (Cham & Redfern, 2004). In addition to these factors, the force-generation properties of the muscles, the anatomical features of the skeletal system (e.g. anthropometric properties, muscle paths) and the underlying neuronal control system, contribute substantially to generating the force to perform the tasks, such as supporting body weight, walking and carrying (LaFiandra et al., 2003).

4. Ergonomics measures in WWAL

In manual assembly systems, the focusing on only single aspects of ergonomics human performance measures may lead to conflicting conclusions in assessment of ergonomics stress level in work situations due to the following reasons (Al-Zuheri et al., 2010b):

- The possible interactions between more than one measure that may lead to conflicting conclusions about certain work hazards for the assemblers if these measures are considered separately,
- The large number of postures and the different exposures during manual assembly operations (as mentioned earlier) that should be considered in ergonomics evaluation, and
- The proposed ergonomically measures are sensitive to changes in the physical structure of workstations and workplaces in assembly systems.

Consequently, for obtaining accurate ergonomics understanding of work activities during manual assembly work, the evaluation process should examine by more than one measure to gain sufficiently precise data. The biomechanical and physiological measurements used have been instrumental in comparing different types of industrial jobs with respect to physical strain and fatigue (Garg et al., 1978; Bossi et al., 2004).

4.1 Ergonomics assessment of WWAL based on physiological and biomechanical models

4.1.1 Physiological model

Energy expenditure varies among assembly workers. The variations are caused by differing tasks involving work on components at various stages and walking from one place to another.

This is the most significant factor contributing to the variation of energy expenditure among assemblers (Honaker, 1996). Thus, average metabolic energy expenditure has been suggested for determining the amount of energy requirement needed to perform a given work without accumulating an excessive amount of physical fatigue (Garg et al., 1978).

Much research has been done estimating the energy expenditure of different assembly tasks (Holt et al., 1990; Chryssolouris et al., 2000; Ben-Gal & Bukchin, 2002; Longo et al., 2006). This research is used to ensure that the reasonable workload expectations are placed on the worker. This model can be used to estimate the energy expenditure of each task in WWAL; the parameters of the task being performed (e.g. object weight, speed, grade, and how a load is carried/moved in the hands/arms, height, etc.) as well as the individual factors such as gender, body weight and time taken to perform each task.

4.1.2 Biomechanical and dynamic motion models

Several biomechanical models have been developed to collect data on the nature of the strain placed on bodily structures and tissues by loads and forces during manual assembly processes (Kumar, 2006). The tools used to gather, and or analyse data in manual assembly works, included lifting limitations according to the National Institute for Occupational Safety and Health (NIOSH) guideline for biomechanical measure (Waters et al., 1994); workers posture during the task according to the Ovako Working-Posture Analysis System (OWAS) guidelines on risk or injury measure (Karhu & Kuorinka, 1977); cycle time from Methods Time Measurement (MTM) (Stevenson, 2002); and Rapid Upper Limb Assessment (RULA) (McAtamney & Corlett, 1993), is a measure for risk factors associated with upper limb disorders; Lifting Strength Rating (LSR) (Chaffin & Park, 1973); the university 3D Static Strength Prediction Program (3DSSPP) (Michigan, 2009); psychophysical approach (Snook & Hart, 1978); Lumbar Motion Monitor (LMM) and Ohio State University (OSU) Model (Davis & Waters, 1998).

Most of the mentioned biomechanical models are used to estimate the muscle forces in static postures. However, the effects of inertia are not accounted in these models; hence static models alone are not considered accurate enough to offer truly predictive data (Granata & Davis, 1999).

Much of the research undertaken on human dynamic motion, has been undertaken utilising the multi-segment models developed to assess moments of force or torque applied about the axes of the joints with the joint at various angles. Most of this research describes the biomechanical modelling of only one part of the body. A small proportion of that research has specifically addressed whole body models for activities involving both lower limbs and the upper body, such as whole body balance control (MacKinnon & Winter, 1993) and weight lifting (Kingma et al., 1996). However, none of this research has been focussed on biomechanical models that simulate dynamic walking and carrying conditions.

4.2 Suggested biomechanical model for the lower limbs of workers walking.

The worker in WWAL walks carrying work-pieces during movement from workstation to another sequentially (from workstation (1) to (2), to the point that the worker reaches the last one, workstation k), during the entire shift time. As stated earlier, this work is often associated with ergonomically poor conditions that result in WRMDs.

Therefore, there is a pressing need to propose a biomechanical model for effectively evaluating workers' capability to perform their required tasks without putting themselves at risk of developing a musculoskeletal injury.

In this research, a biomechanical model for the determination of net muscle moments and forces of lower limbs under dynamic motion conditions associated with performing assembly tasks of WWAL, in particular; walking and work-piece carrying. The resultant force and movements are calculated at the axis of hip, knee and ankle during level walking and carrying loads. In addition, the proposed model is used to investigate the possible effects of variables on the walking performance of workers during load-carriage tasks. These variables include walking speed and the weight of the work-piece carried.

Details of this model were fully described by Winter (Winter, 1980) and were validated by Flanagan and Salem (Flanagan & Salem, 2005) via comparing a top-down to a bottom-up study of squatting through measuring of net joint moments.

5. Materials and methods

5.1 The model: Net support moment approach

Biomechanical studies often total individual joint kinetics measurements (such as the net joint moment or net joint moment power) to obtain one biomechanical measurement of lower limb functions (Flanagan & Salem, 2005). However, it has been proposed that the net joint moments at the hip, knee, and ankle be collated into a single measure called "net support moment" (Winter, 1980).

The need for such a measure is justified (according to Winter), by the actual moments in the strength level required to walk, stand and recover from a slip etc. In addition, Winter found that some form of internal compensation was present. For example, when hip moment was high, knee moment or ankle moment was low, and vice versa. Consequently, interpreting the three moment curves in study as shown in figure 2, led him to suppose that the sum of all three moments (represent by support moment) plays a significant role in preventing a collapse of the knee.

Additionally to the above, Winter classified the joint moments to be positive when the pulling direction is counter clockwise and negative when clockwise, as shown in figure 3.

Equation 1 shows the net supporting moment calculated by summation of the three net joint moments (Winter, 1980):

$$M_s = M_k - M_a - M_h \quad (1)$$

Where M_s the net support moment, M_k , M_a and M_h are the moments at the knee, ankle and hip respectively. Assuming that the thigh and shank are equally long, the support moment was redefined by Hof (Hof, 2000). With same postulation of moment polarity, the new equation proposal by Hof is:

$$M_s = \frac{1}{2} M_a + M_k + \frac{1}{2} M_h \quad (2)$$

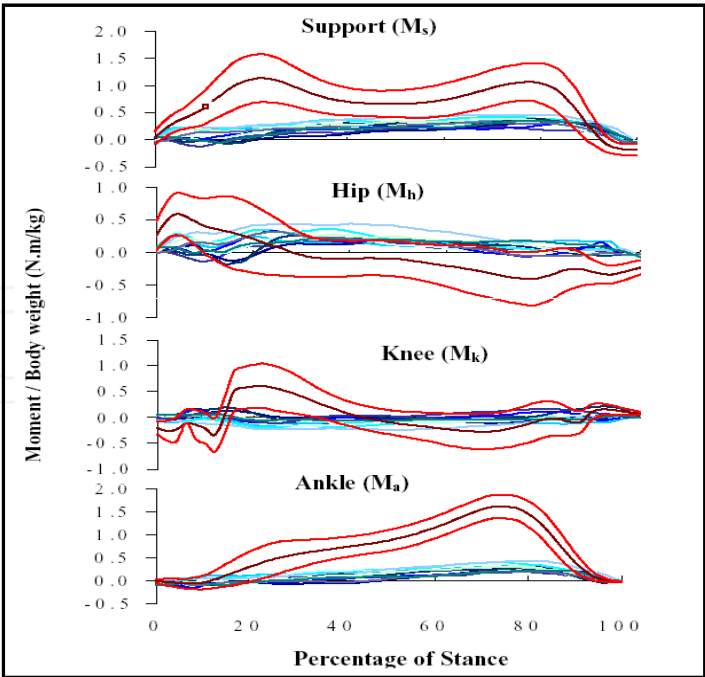


Fig. 2. Support and joint moments of force at hip, knee and ankle during walk (Winter, 2005).

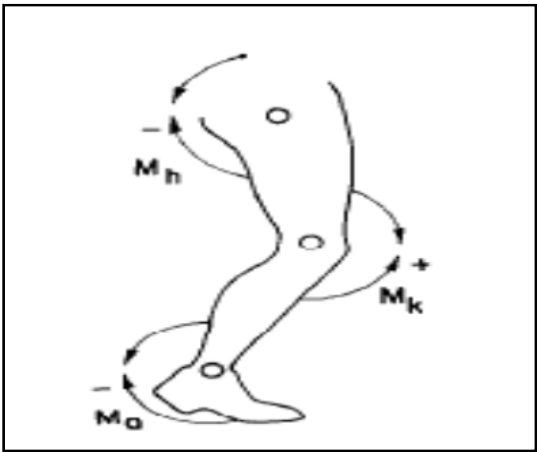


Fig. 3. Profile of joint moment of force at the ankle, knee and hip during walking (Winter, 2005).

This measure is commonly used for the assessment of mechanical output by lower limbs during walking (Winter, 1980; Hof, 2000), and in other activity such as sitting and standing (Yoshioka et al., 2009). While collating individual joint kinetic measures into a single measure (net support moment) has been used to characterize the mechanical demands of the lower limb across many activities, the validity of this single measure during dynamic occupational task like those in WWAL is still questionable.

Throughout this research, the goal of “net support moment” measure in an ergonomics context is to gain information about the overall mechanical demand placed on the muscles that cross each joint of lower limb. In other words, this measure is considered as the index for assessing the degree to which lower limb joints of the body are strained during manual tasks in WWAL.

5.1.1 Biomechanical modelling strategy

Biomechanical research uses laws of physics and engineering concepts to describe the motion undergone by the various body segments and forces during normal or abnormal activities. As a general approach, the human body is treated as a mechanical system, made up of rigid links (the bones) that are connected at joints. (Chaffin, 1969; Garg et al., 1982; Chaffin & Andersson 1990; Yanxin Zhang, 2005; Chaffin, 2007) have been presented a set of linked segment models of the human body that can be used to estimate forces and mechanical moments (torques) imposed on the system during work activities.

In these models, a part of the human body is modelled as a chain of rigid body segments, interconnected by joints. Intersegment reactive forces and moment loads at each joint of body member are calculated by applying Newton’s second law and Euler’s equations. Generally in Newton-Euler mechanics, the applied forces (i.e., body segment weights and hand loads) are multiplied by their perpendicular distance from joint centres (i.e. moment arms). Figure 4 illustrates many of the force and moment vectors at specific joints of the body including (hand, knee, elbow, ankle, shoulder, foot, and hip) can be calculated by the similar way (Michigan, 2009).

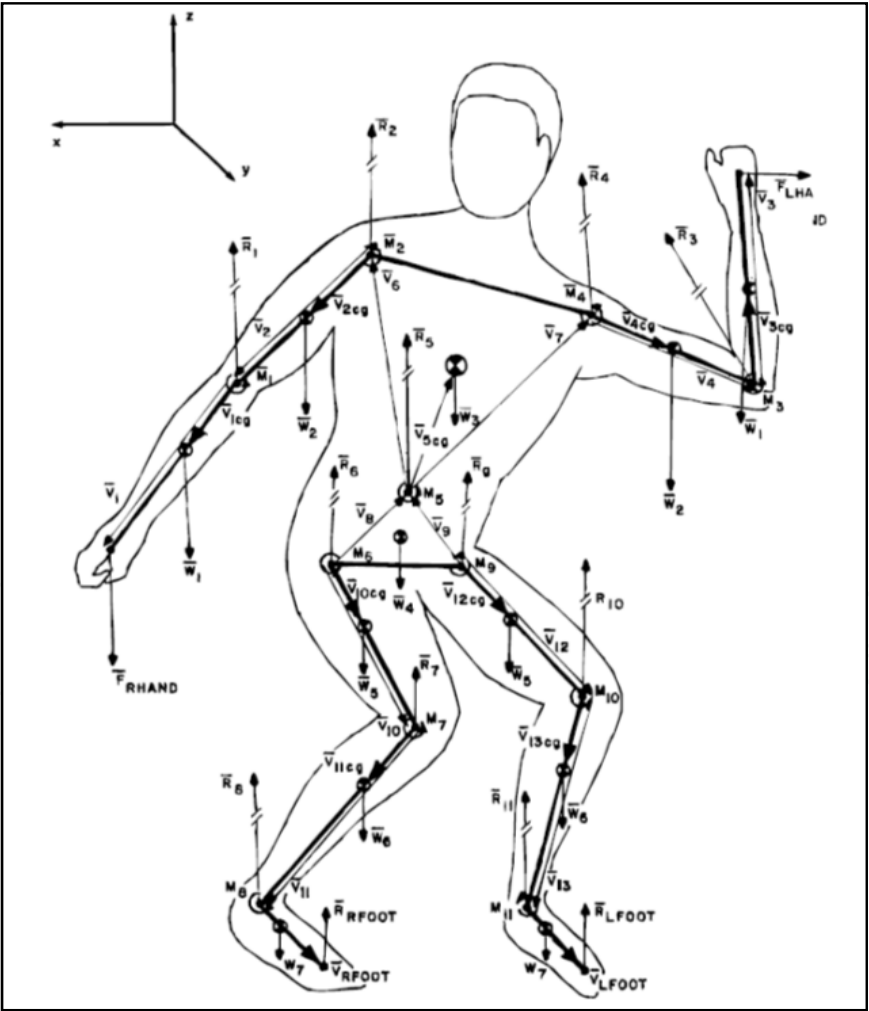


Fig. 4. Schematic representation of the strength model developed to calculate the muscle strength requirements needed to perform specified manual operations (Michigan, 2009).

Dynamic biomechanical analyses have been used in researches on walking and other activities such as lifting or carrying. In these analyses, inverse dynamics method is used to compute the joint moments of force in the lower limb (Redfern et al., 2001; Miller, 2002).

5.1.2 Newtonian model of the lower limb

The general logic that is used to predict forces and moments in lower limb joint during various jobs of WWAL is described in figure 5.

Accurate estimation of joint forces and moments of the lower limb during the occupational tasks of WWAL is mainly dependant on the accurate measurements for the static and inertial load during worker movement. The static load can be calculated by measure the following (Chaffin & Andersson, 1990; Wu & Ladin, 1996; Zijlstra & Bisseling, 2004):

1. Positions of the body segments, and
2. Foot-ground reaction force and moment.

While the calculation of inertial load due to requires kinematic description of the lower limb involves:

1. The position and orientation (joint angles of hip, knee and ankle), and
2. Walking speed and acceleration.

The above data describes the movement pattern (kinematic data) and the forces which cause that movement (kinetic data). Based on these data, an inverse dynamics method is applied in estimating the determinants of worker lower limb, such as the reaction forces in joints.

The method of inverse dynamics is used to derive the parameters of worker lower limb walking, starts from the foot segment toward the thigh segment with the motion data and the human body segmental characteristics that introduced in previous studies such as (Chaffin & Andersson, 1990; McLean et al., 2005).

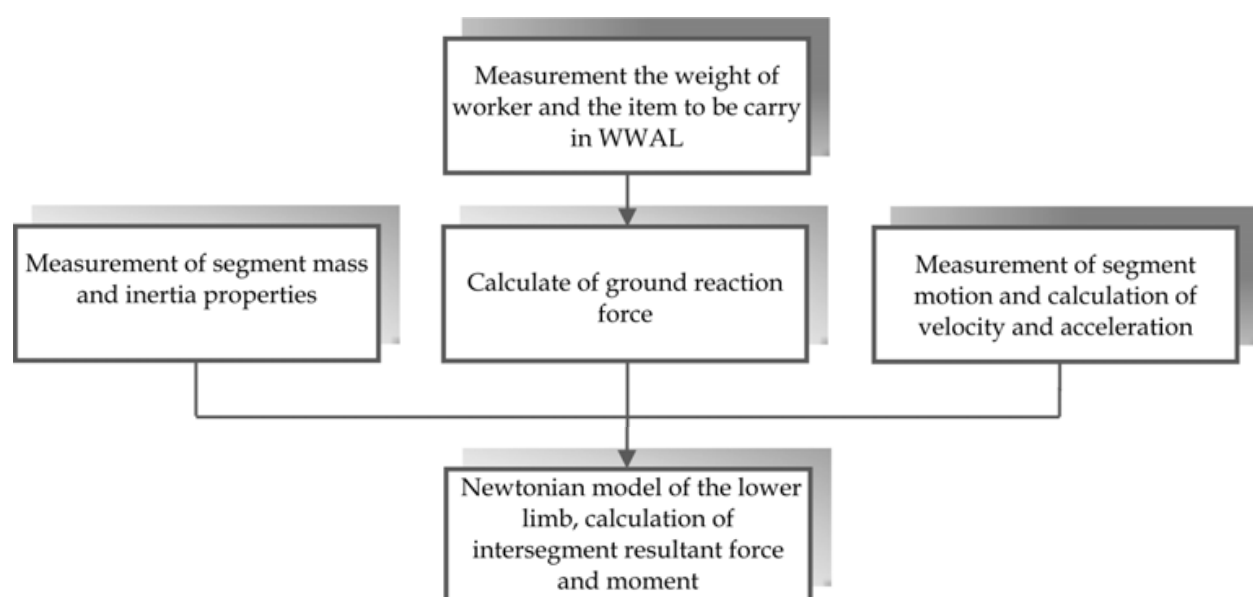


Fig. 5. Procedural steps in the prediction of joint forces and moments of the lower limb.

5.1.3 Assumptions

The model represents the movement of a lower limb of the human body. The three segment; foot, knee and thigh are treated as three rigid links as illustrated in figure 6. The joints included in the model are; ankle, knee and hip. Each leg has six Degrees of Freedom (DOF); three DOF at hip (flexion-extension, abduction-adduction and internal-external rotation), one DOF at knee (rotation about a fixed flexion-extension axis) and two DOF at ankle (rotation about talocrural and subtalar joint axes) (McLean et al., 2005). Given the weight of the work piece, inertial property of the segments, and length of the segments, the model is based on assumptions for appropriate approximations. These assumptions include:

1. The model for the sagittal plane, also can be applied in the frontal plane,
2. The model considers the two-handed asymmetric load -carrying during WWAL tasks,
3. The force of the load (the weight of work-piece to be assembled) passes through the central of mass of the hand,

The model is also based on several assumptions made regarding the muscle activity of the ankle, knee and hip, which follows in preceding studies of (Lin, 1995; Winter, 2005; Yanxin Zhang, 2005):

1. The centre of mass location of each segment remains fixed in the segment during the movement,
2. The worker body has not change in mass,
3. Throughout the movement, the length and cross-sectional area of each segment remains constant,
4. The joints are frictionless, and
5. Joints are considered to be hinge (2D motion) or ball and socket (3D motion).

The dimensions, mass, and internal properties of lower limb segments are assumed to conform to those proportions of anthropometric data provided in (Chaffin & Andersson, 1990; Winter, 2005).

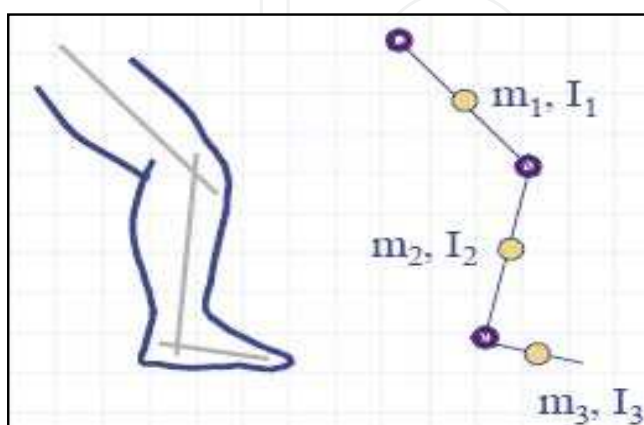


Fig. 6. A schematic representation of the lower limb segments where m_1 , m_2 and m_3 and also I_1 , I_2 and I_3 represent the mass and moment of inertia to the thigh, shank and foot respectively.

5.1.4 Model parameters

1. **Ground reaction force:** The forces which interact between the human foot and the ground in walking or running are referred to as Ground Reaction Force (GRF), as shown in figure 7. The GRF causes (Giddings et al. 2000):
 - a. A forward acceleration on the body, and
 - b. A moment about the vertical axis of body.

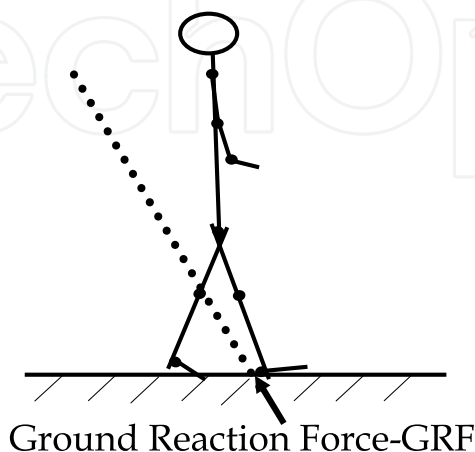


Fig. 7. Projection of GRF vector that is used to predicate the joint moments of force at the lower limb (reproduced from Winter, 2005).

The GRF can be calculated by using dynamic equations (Okada et al., 2006). The intersegment resultant forces and moments at the ankle, knee and hip are significantly dependent upon the magnitude of the GRF and its location relative to the joint centre for each. (Johnston et al., 1979). A number of researchers have examined GRF during walking (Redfern et al., 2001).

2. **Joints force and moment:** The control of walking is a result of the interaction of forces acting on human body. These forces can be internal or external. Internal forces refer to the inertial loads of the body segments which are related to the segmental acceleration. External forces on the body refer to gravitational and external loads (or static loads) due to the body contact with the environment (Wu & Ladin, 1996). In conclusion, the first one generates individual body segment movements, while the second affects whole body movements. The joint moments can be created by concentric and eccentric muscle contractions (Simonsen et al., 2007).
3. **Mass segments and inertia:** The inertia of the body segments is changed due to the non-uniform horizontal component of the propulsive force. Fluctuation in the amount of applied force will lead to change in the Centre of Gravity (COG) of the body segments. Variances in COG depend upon periods of speeding up and slowing down of the body segments (Cham & Redfern, 2004). Thus, the inertia of body segments changes also during the various activities of WWAL. The calculations of mass and inertial properties of each segment based on anthropometric measurements were made on the subjects as mentioned above.

The equations to calculate the joint forces and the moments and moment of inertia are described in next section.

5.1.5 Model formulation: Joint moments calculation

The drawing below (fig.8) is a Free-Body Diagram (FBD) representing the lower limb of a worker. The FBD demonstrates all the forces and moments that exist on the foot, shank and thigh. The equations derived to solve the resultant forces and moments are described below.

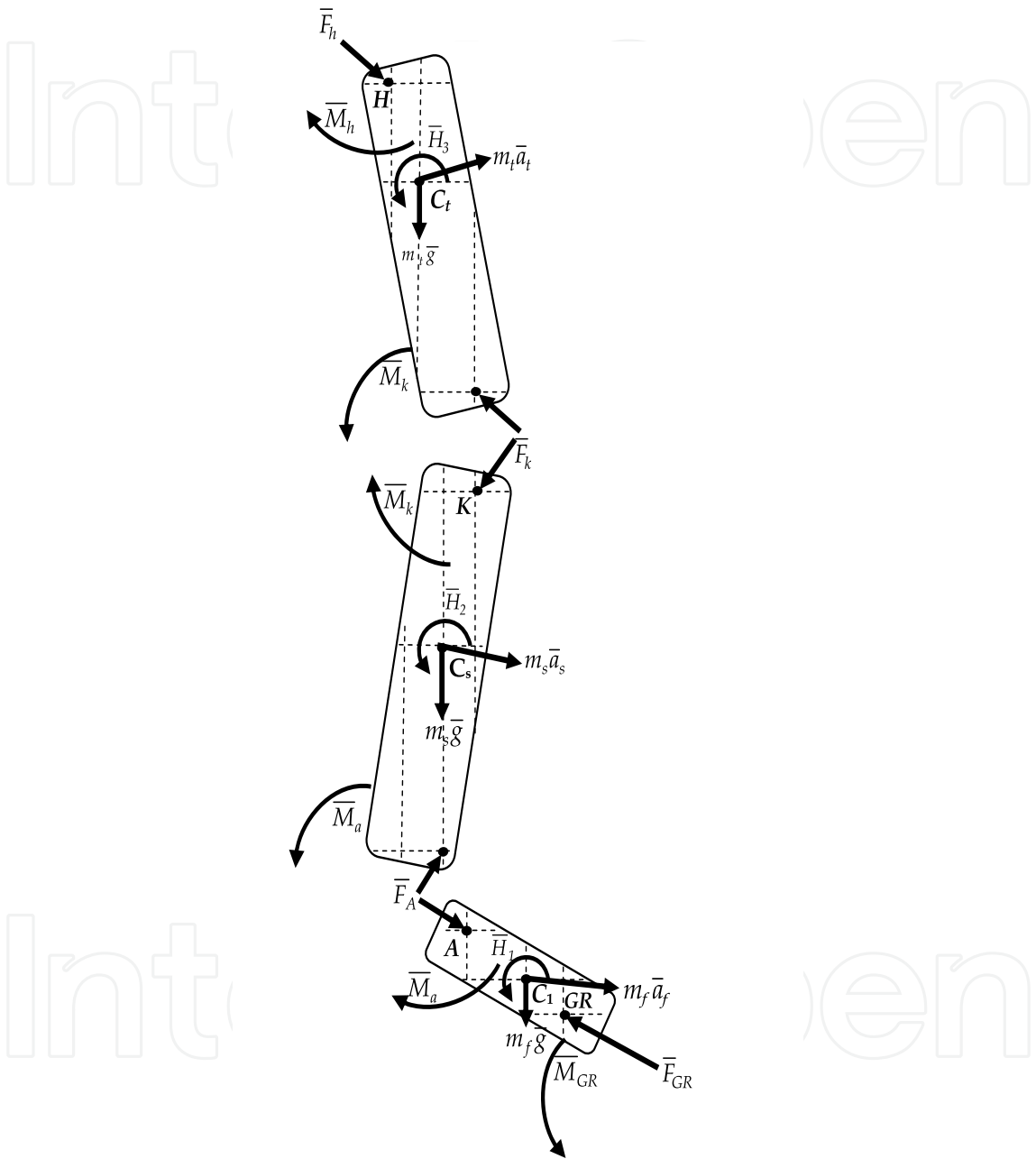


Fig. 8. The FBD of lower limb depicted with the intersegment resultant force and moment at hip, knee and ankle during walking.

Using inverse dynamics and the free body lower limb, much research concerned with the calculation of joint moments about the ankle, the knee and the hip joint (Hardt,

1978; Johnston et al., 1979; Wu & Ladin, 1996; Winter, 2005; Simonsen et al., 2007). This research uses slightly modified version of the formula presented by Johnston (Johnston et al., 1979). The resultants forces for the ankle, hip and knee are calculate as follows:

$$\bar{F}_a = m_1(\ddot{a}_1 - \bar{g}) - \bar{F}_{GR} \quad (3)$$

$$\bar{F}_k = \sum_{i=1}^2 [m_i(\ddot{a}_i - \bar{g})] - \bar{F}_{GR} \quad (4)$$

$$\bar{F}_h = \sum_{i=1}^3 [m_i(\ddot{a}_i - \bar{g})] - \bar{F}_{GR} \quad (5)$$

Where:

\bar{F}_{GR} = Ground reaction force acting on foot (kg),

\bar{F}_j = Intersegment resultant force at the joint (j) (kg),

m_i = Mass of segment (i) (kg),

\ddot{a}_i = Acceleration vector of the centre of gravity of segment (i) (m/sec²), and

\bar{g} = Acceleration vector due to gravity, 9.8 m/sec².

The sagittal plane joint moments that generated at the ankle, knee and hip can be computed using the following equations:

$$\bar{M}_a = \dot{\bar{H}}_1 - [\bar{r}_{A_{C_1}} \times m_1(\ddot{a}_1 - \bar{g})] - \bar{M}_{GR} - (\bar{r}_{GR_A} \times \bar{F}_{GR}) \quad (6)$$

$$\bar{M}_k = \sum_{i=1}^2 \left\{ \dot{\bar{H}}_i - [\bar{r}_{K_{C_i}} \times m_i(\ddot{a}_i - \bar{g})] \right\} - \bar{M}_{GR} - (\bar{r}_{GR_K} \times \bar{F}_{GR}) \quad (7)$$

$$\bar{M}_h = \sum_{i=1}^3 \left\{ \dot{\bar{H}}_i - [\bar{r}_{H_{C_i}} \times m_i(\ddot{a}_i - \bar{g})] \right\} - \bar{M}_{GR} - (\bar{r}_{GR_H} \times \bar{F}_{GR}) \quad (8)$$

Where:

\bar{M}_{GR} = The moment due to of the ground reaction force (kg),

\bar{M}_i = Joint moment vector about joint (j),

C_i = Position of centre of mass of segment (i) (meter),

\bar{r}_{j_i} = Position vector from joint (j) to the centre of gravity of segment (i) (meter), and

$\dot{\bar{H}}_i$ = Inertial component vector of the joint moment about joint (j) (kg.m²).

The moment of inertia about the pivot point of joint (j) can be calculated by using the following equation derived from the basic mechanics:

$$\dot{\vec{H}}_i = I_i \times \vec{\alpha}_i \tag{9}$$

Where:

I_i = Moment of inertia of segment (i) about the centre of mass (kg.m²), and
 $\vec{\alpha}_i$ = Angular acceleration vector of segment (i) about the centre of mass (rad. /s²).

The following points were taken as positions for the lower limb joints centres:

A = Position of ankle joint centre (meter),
 K = Position of hip knee centre (meter),
 H = Position of hip joint centre (meter), and
 GR = Position of ground reaction force effect (meter).

5.2 The hypothetical assembly line

This research considers a U-shaped manual assembly line using walking worker approach and multifunctional workers to assemble a single model product (hydraulic valve actuator). The line is depicted in figure 9. The weight of hydraulic valve actuators that is assembled and handled manually at first workstation is 4.96 kg. Table 1 summarizes the example at each workstation in terms of the weight of the valve actuator after assembly process at each workstation on the line.

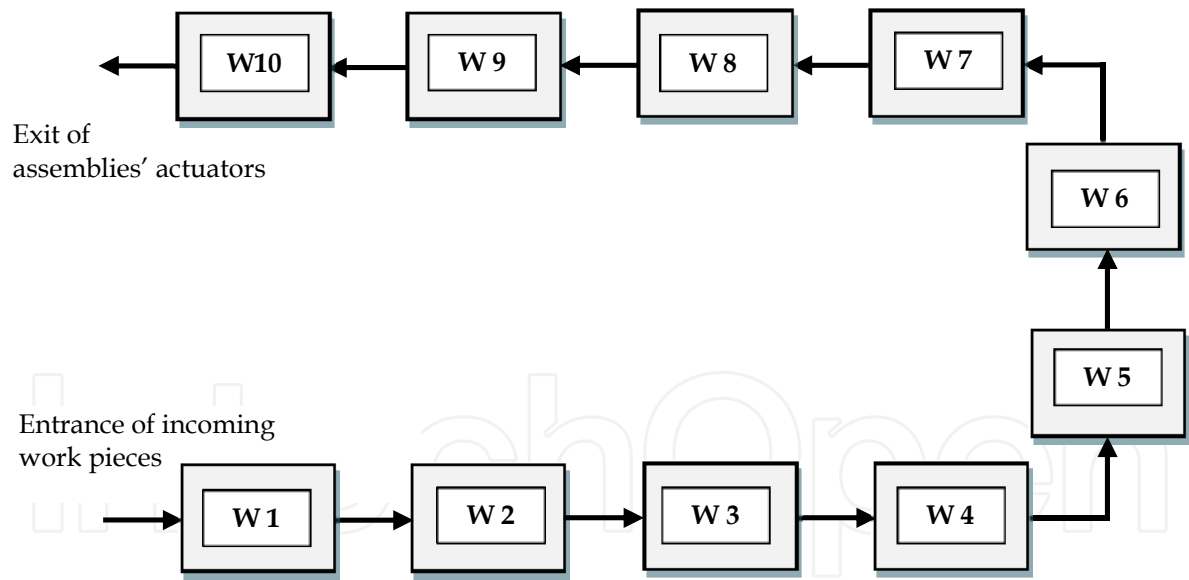


Fig. 9. U-shaped assembly line of hydraulic valve actuators for (m) workers and (k) workstations.

The work-piece is processed at workstations w_1, w_2, \dots, w_{10} , sequentially, and departs from the line as a finished product. The worker arrives at workstation w (any workstation on the line) to perform the specified processing of the part assemblies at that workstation. When the operation at workstation w is accomplished, then he walks toward next workstation and carries out the essential assembly work as scheduled and continues until the product is built completely at workstation w_{10} . The worker then moves back to the first

workstation w1 to begin the assembly of a new product with the same previously described procedure. The products being assembled are transported manually by workers between workstations of assembly line.

Workstation s	Weight of actuators after process (Kg)
k 1	4.96
k 2	5.70
k 3	6.27
k 4	7.22
k 5	7.58
k 6	7.96
k 7	8.750
k 8	9.63
k 9	9.63
k 10	9.63
	Final weight of actuator = 9.63Kg

Table 1. The weight of the actuator (the work-piece) at each workstation on the line

5.3 Experimental data and procedure

Part of this research was performed based on previously published data on the calculation of net summation of the moments at three joints (hip, knee and ankle), support moment (Winter, 1980; Hof, 2000). That data includes; (1) segmental relative weight, centre of gravity and moment of inertia data for the (hypothetical) workers as shown in table 2; (2) the resolution of the position of the body from the angles at each articulation; (3) the determination of the angular velocities and angular accelerations at each articulation, which in turn, gives the linear acceleration of the body links.

It is based upon the assumption that the average weight of workers is 82 kg. The procedure of modelling includes two stages. Firstly, the calculation stage; this consists of several steps; (1) the calculation of inertial forces and inertial resistance moments due to acceleration: (2) calculation of moments and forces on the body from the motion input data (i.e. the x-y joint position data over time for the ankle, knee and hip); (3) the calculation of reactive moments and forces at each articulation exerted by the muscles to overcome the resultant forces due to external loads and body weight; and (4) the joint moments of all lower limb joint moments (hip, knee, and ankle) and also support moment were calculated.

In the second stage, on the basis of inputting walking speed and the weight of the work piece, the effect of these variables at lower limbs joints is estimated. The model application consisted of using this data with two walking speed with carrying work-piece to be assembled; (1) slow walking (0.7 meter/sec.) and (2) fast walking (1.4 meter/sec.). The initial weight of work-piece is 4.96 kg, increasing gradually with assembling process to reaching a final weight of 9.63 kg at workstations 8, 9 and 10. The carrying technique is front with two-hand.

Segment	Relative Weight	Centre of Gravity	Moment of Inertia about CG (kg.m ²)
Head	0.073	46.4% vertex to chin	0.0248
Trunk	0.507	38.0% shoulder to hip	1.2606
Upper Arm	0.026	51.3% shoulder to elbow	0.0213
Forearm	0.016	39.0% elbow to wrist	0.0076
Hand	0.007	82.0% wrist to knuckle	0.0005
Thigh	0.103	37.2% hip to knee	0.1052
Calf	0.043	37.1% knee to ankle	0.0504
Foot	0.015	44.9% heel to toe	0.0038

Table 2. Segmental relative weight, centre of gravity and moment of inertia data

6. Results and discussion

6.1 Joint moments

For the stance phase normalized to 100%, figures (10-b, 10-c and 10-d) represent the lower limb joint moments (hip, knee and ankle joints) on the sagittal plane for a single worker in WWAL during complete posture cycle under both normal walking and different work-piece carrying conditions. As illustrated in that figure, changes in the relative shape and magnitude were found in moment of hip, knee and ankle joints among different weights carrying (4.96, and 9.63 kg) and also basically when workers walking without carrying any work-piece.

Among the three lower limb joints, the hip moment, which was consistently and significantly more biased with increasing work-piece weight during the 0-10% of the gait cycle. This can be explained by the fact that the positive hip joint angular impulse for the contralateral side tended to increase with the increase of work-piece weight.

From the results of this research, it was found that when workers walked at different speeds carrying work- pieces, the moment of the lower limb joint would increase with the walking speed (figure 11). This is because the percentage of the stance phase decreased as the walking speed increased and the swing phase increased as the walking speed increased. Figure 10 presents the M_s and the contributions to the M_s of each joint for the stance phase normalized to 100%.

6.2 Net support moment

Figure 10 presents the contributions of each lower limb joint for the net support moment in carrying different work-piece weights as well as in normal walking. At the initial stage of the gait cycle (0-10%), the hip and knee joint moments were large. On the other hand, during that stage the ankle joint moment was nearly zero. Therefore, the hip and ankle contributed to the most part of the support moment throughout the stance phase.

Net support moment was considerably reduced and even in negative values throughout the swing phase (50-100% of the gait cycle). This is because of the negative values of the hip moment in end of stance phase. From approximately 40% to 100% of the gait cycle, the knee and the ankle moment contributed positively to support the body-mass of worker during the job.

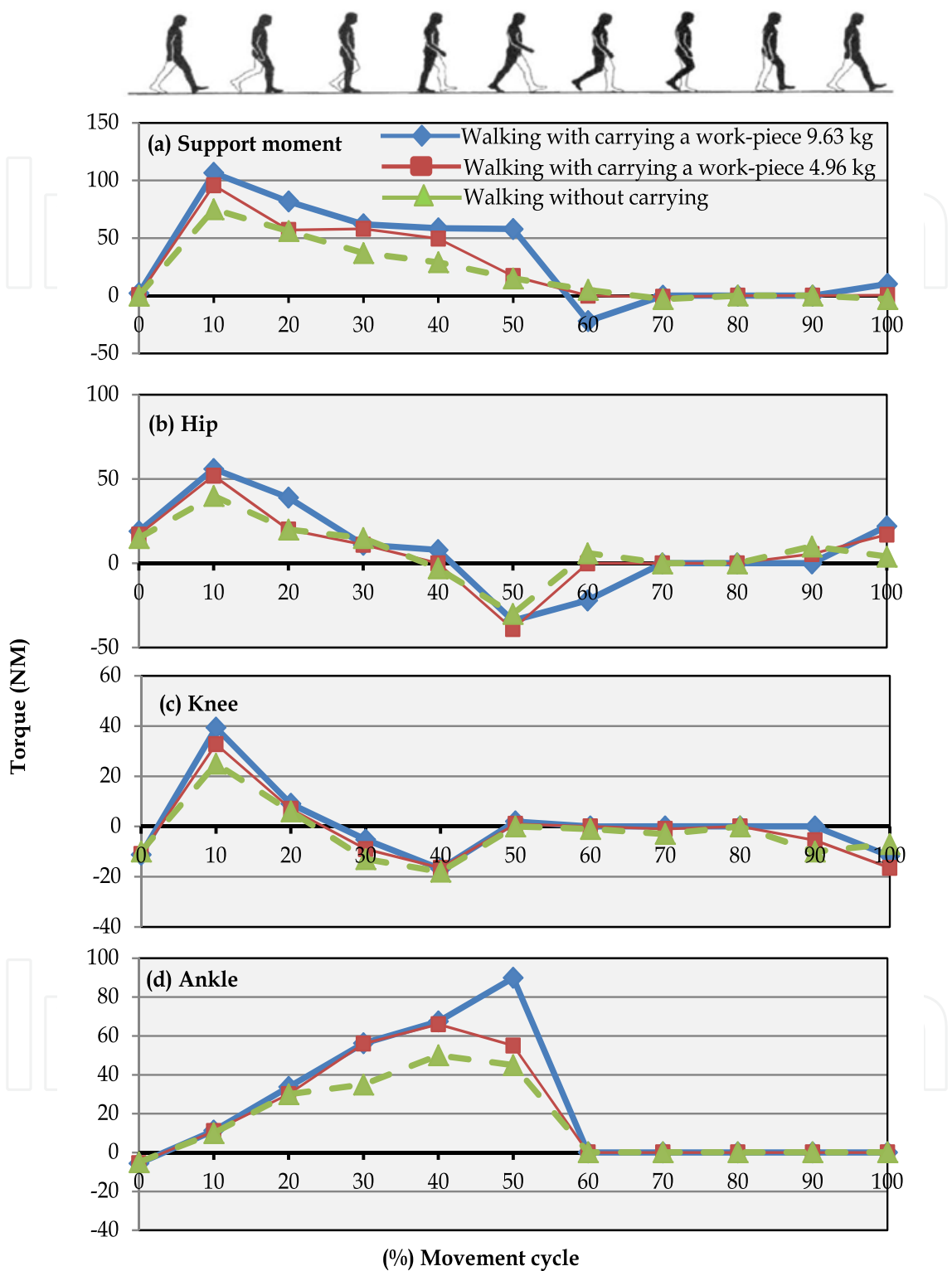


Fig. 10. The calculated net support moment M_s according to the original definition of Winter and the resulting moment about the (b) hip moment; (c) knee moment and (d) ankle moment. The calculations were performed for different loading condition (as shown in legend). Workers data: male, 34 years, weight 82 kg and walking speed 0.7 m/sec.

From figure 11, it was evident, that support moment varies quite considerably when walking speed was increased from 0.7 to 1.4 meter/sec. This can be explained by the fact that both the GRF and the knee angle in stance are strongly dependent on walking speed. As expected, there was a significant increase in net support moment throughout the walking from workstation to another (figure 11). However, this was related significantly to increasing weight of work-pieces during assembly due to the addition of new components at to the work-piece at each workstation.

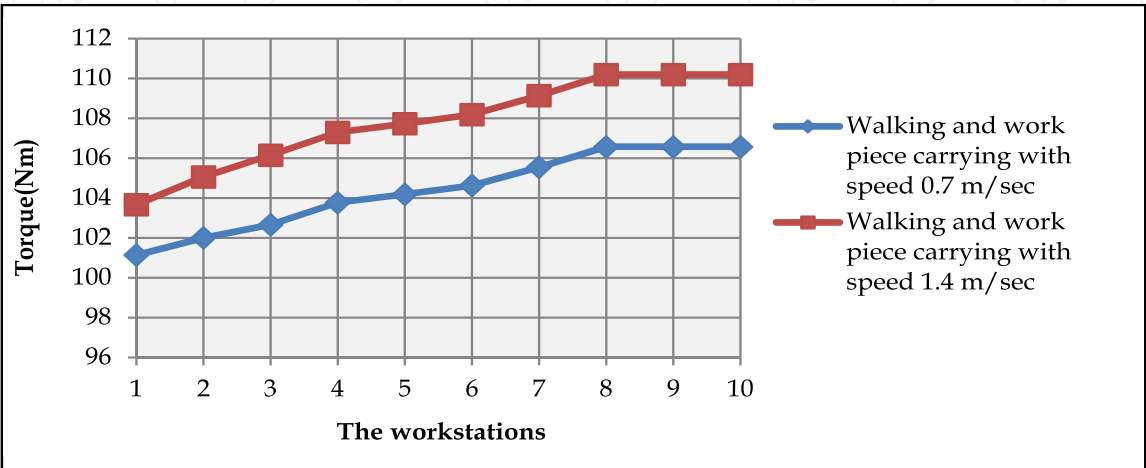


Fig. 11. Net support moment M_S at WWAL workstations, for two different carrying condition during the 10% stance period of movement cycle where the M_S at that time reaches to the maximum value as the results indicated in figure 10.

6.3 Ground reaction forces

Ground reaction forces in walking increased significantly with work-piece carrying (figure 12). More specifically, carrying a 4.96 kg weight of work-pieces at first workstation and then increased to 9.63 kg load led to increases in the peak normal ground reaction force ranging from -75 to -50 N and to -50 from the normal walking, respectively.

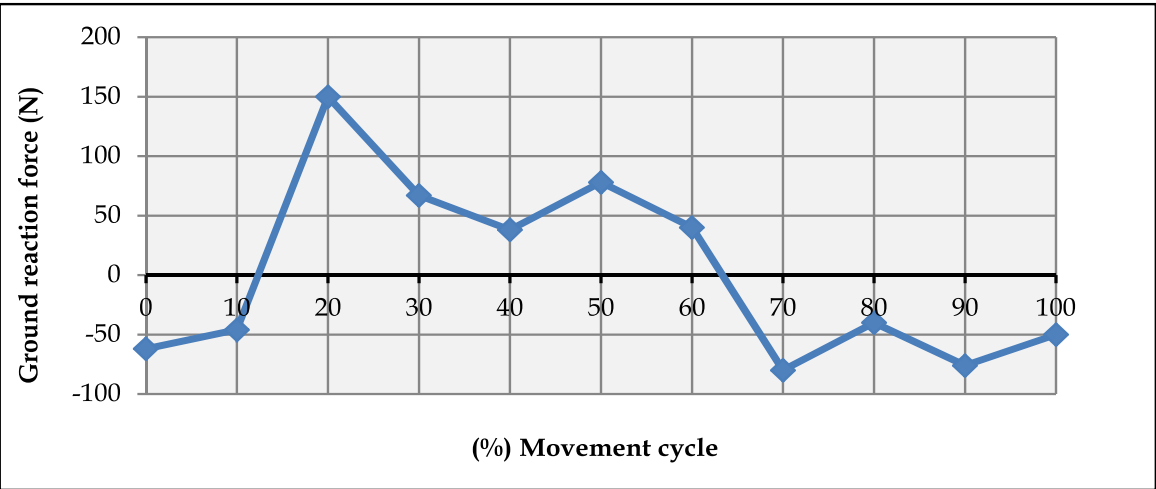


Fig. 12. Calculated ground reaction force during complete movement cycle (0-100%) while walking with carrying 4.96 weight for work-piece.

Normally, ground reaction forces depend on body mechanics, mass, and acceleration at the time when the individual touches the ground. Consequently, as mass (weight of work-piece) increases, ground reaction forces generally increase. Also, a worker's gait pattern affects ground reaction forces. As a result, intensity, mass, speed and type of activity were expected to be significant fixed effects.

7. Conclusion and further work

The net support moment model, described by Winter in 1980, provides a useful framework to study the strategy used to support body weight during walking while performing a job in dynamic production systems like WWAL. In this research, the model was used to predict the moments for the hip, knee and ankle during walking and carrying different work-piece weights, as well as normal walking. In addition to work-piece weight, the effect of walking speed of walker on support moment was also investigated. In conclusion, the results of this research indicated that, the net support moment and the contributions the hip, knee and ankle moment respectively, is an interesting method to assess the weight bearing and walking speed strategies for walking workers.

The net support moment is calculated by summation of the moments at hip, knee and ankle during walking. This enables a designer to construct a layout of WWAL in such a way as to obtain optimal movement, i.e. the movement in which the net support moment of all three joints is minimized.

The reliability of the presented predictive model as a tool to investigate the mechanical demands of the lower limbs during dynamic occupational task like those in WWAL is still questionable. To enable the use of this model, it needs further work in two areas; (1) model validation by comparing the predicted results with the actual measurement data for dynamic walking whilst carrying a work-piece, (2) further investigation of the relationships of other variables during walking of worker with work-piece carriage, such as gender and the physical design of workstations.

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9. References

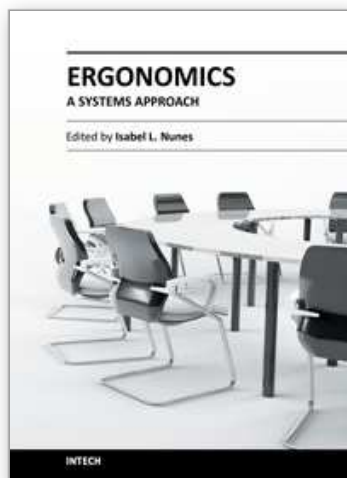
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Ergonomics - A Systems Approach

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This book covers multiple topics of Ergonomics following a systems approach, analysing the relationships between workers and their work environment from different but complementary standpoints. The chapters focused on Physical Ergonomics address the topics upper and lower limbs as well as low back musculoskeletal disorders and some methodologies and tools that can be used to tackle them. The organizational aspects of work are the subject of a chapter that discusses how dynamic, flexible and reconfigurable assembly systems can adequately respond to changes in the market. The chapters focused on Human-Computer Interaction discuss the topics of Usability, User-Centred Design and User Experience Design presenting framework concepts for the usability engineering life cycle aiming to improve the user-system interaction, for instance of automated control systems. Cognitive Ergonomics is addressed in the book discussing the critical thinking skills and how people engage in cognitive work.

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