The Ergonomics of Manual Material Handling

Pushing and Pulling Tasks

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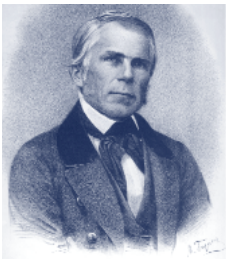
I Introduction

Carts and mobile equipment are used in nearly every industry. Medication, supplies and patients are moved about a hospital on wheeled devices; process equipment is often on wheels to allow for greater flexibility in lean manufacturing facilities; office supplies and mail are delivered by cart, and most office chairs are fitted with casters. Nearly all manufacturing and distribution facilities rely on a variety of wheeled carts and equipment throughout their processes.

Wheeled equipment is often taken for granted and selecting the right designs, including wheels and casters, is often overlooked. Careful forethought in the design of pushing or pulling tasks, on the other hand, will result in measurable bottom-line improvements. Without this care, the resulting costs to your company may be significant. This White Paper provides an overview of the issues involved in manual pushing and pulling, including ergonomics; cart, wheel, and caster design; and important operating environment factors.

Wojciech Jastrzebowski, a Polish scholar, first used the term ergonomics in 1857. He derived it from the Greek words ergon (work) and nomos (principle or law) to mean the Science of Work. Ergonomics has since evolved into an important bottom-line opportunity that affects all competitive businesses, and extends well beyond the workplace into our daily lives. In business terms: er·go·nom·ics \,ûrg-go-‘näm-iks\ – Ergonomics removes barriers to quality, productivity and safe human performance by fitting equipment, tools, tasks, and environments to people.



A. The Economics of Ergonomics

Health and safety issues are perhaps the most talked about costs and consequences related to ergonomics, yet ergonomics historically grew from the business realm of efficiency and quality improvements. Today, business and social forces have driven the science to encompass a large set of concerns, including productivity, quality, and health and safety (Figure 1). Each of these work factors has an associated cost, and, alone or together, they may carry a large hidden price tag for your company.

Figure 1. A poor match between people, work, tool, and equipment design has financial costs in at least three areas: productivity, quality, and health and safety.

B. Ergonomics, Productivity, and Quality

Ergonomics has deep roots in the productivity improvements that characterized much of the technology advancements of the 1900s. Fredric Taylor achieved dramatic productivity improvements in the steel industry by studying the optimal relationships between specific tools and tasks and the people who used the tools to perform the tasks. He was able to maximize the amount of material handled in a day, reducing wasted effort and increasing employee job security and compensation in the process.

By studying micromotions in great detail, Frank and Lillian Gilbreth were able to assign reliable time estimates to each type of task (e.g., reach, grasp, move, release). Their work provided a framework in which to define and monitor productivity as it relates to human task motions.

Any ergonomics intervention must be viewed in light of its effect on productivity, and the best ergonomics solutions will often improve efficiency. Simply put, reducing unnecessary or awkward postures and forces almost necessarily cuts the time and effort it takes to complete a task.

Body motions, visibility, workload, and other important ergonomic parameters will also affect the quality of work and the quality of work product. When a task is matched with the ability of the people who perform it, they make fewer errors and produce less waste.

C. Ergonomics, Health, and Safety

Musculoskeletal Disorders (MSDs) are injuries and disorders of the muscles, nerves, tendons, ligaments, joints, cartilage, and spinal discs. Examples include rotator cuff tendonitis, herniated or ruptured lumbar discs, and carpal tunnel syndrome. MSDs can be directly and indirectly related to aspects of the work or the work environment known as risk factors. Non-work activities and environments that expose people to these risk factors also can cause or contribute to MSDs. When an MSD is associated with work it is usually referred to as a Work Related Musculoskeletal Disorder (WRMSD or WMSD). Other similar terms include cumulative trauma disorder (CTD), repetitive stress injury (RSI), and repetitive motion injury (RMI). MSD risk factors can be defined as actions in the workplace, workplace conditions, or a combination thereof that may cause or aggravate an MSD. Examples include forceful exertion, awkward postures, repetitive exertion, and exposure to environmental factors such as extreme heat, cold, humidity, or vibration. Often, a combination of these risk factors over time can lead to pain, injury, and disability. These risk factors can be reduced through informed purchasing and workplace design, retrofit engineering controls, administrative controls, work practice definitions, or in some cases, personal protective equipment.

The manner in which a risk factor leads to an injury/disorder is usually through the accumulation of exposure to risk factors. An event such as pushing or pulling a cart may stress soft tissues in the arms, shoulders, back, or legs, but the exposure may be too low for traumatic injury, and the tissues recover. Repeated exposure to this stress, on the other hand, may interfere with the normal recovery process and produce disproportionate responses and eventually an MSD-type injury.

Corporate initiatives designed to identify and control workplace ergonomic concerns have proven to be effective in reducing the incidence of MSDs and have been efficient investments producing measurable bottom-line benefits.

III The Ergonomics of Pushing and Pulling

Manual Material Handling (MMH) tasks are physical work activities that involve exertion of considerable force because a particular load is heavy or the cumulative loads during a workday are heavy. Examples of MMH tasks include lifting or lowering, carrying, and pushing or pulling. This paper focuses specifically on pushing and pulling activities while using a cart or equipment with wheels or casters.

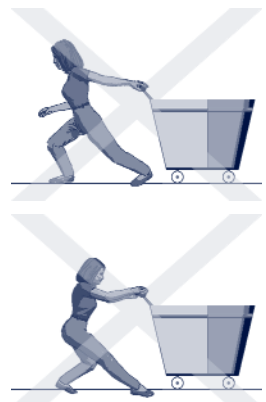
Researchers have identified a number of key factors that must be considered when designing manual pushing and pulling tasks. Surprisingly, as the following case study shows, the weight of the load or equipment, though significant, is not as important as most people think. It is the horizontal push force that matters most, and with the right caster selection and job design, thousands of pounds can be moved safely and efficiently.

Pushing is preferable to pulling for several reasons. You may, from your own experience, recall that your feet are often "run over" by the equipment when pulling. If a person pulls while facing in the direction of travel, the arm is stretched behind the body, placing the shoulder and back in a mechanically awkward posture, increasing the likelihood of painful, debilitating, and costly injury. Alternatively, pulling while walking backwards is a recipe for an accident, because the person is unable to view the path of travel. Further, research demonstrates that people can usually exert higher push forces than pull forces. In some situations, pulling may be the only viable means of movement, but such situations should be avoided wherever possible, and minimized when pulling is necessary.

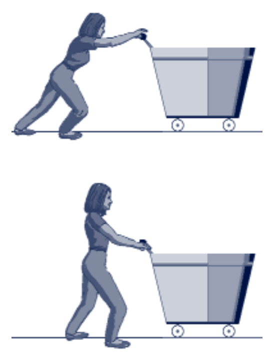
This paper refers to the person pushing or pulling (the operator) as "she." This is to emphasize an important point when designing a manual handling task: when the application of force is required in a task, it is often best to design for the smaller female members of the population, because if they can do it, presumably so can most other woman and men.

Figure 2. Given the choice between pushing and pulling, a task should be designed for pushing.

AVOID PULLING



PUSHING IS PREFERABLE



Case Study

Applied Materials Moves 7,000 lb. Equipment with Ease

Ergonomics engineers at Applied Materials, a manufacturer of silicon chip processing equipment, saw an opportunity for improvement on several fronts when they observed workers moving pieces of equipment that weighed up to 7,000 lbs.

When they started the project, four workers were needed each time the equipment was pushed. Each system was typically moved 10-14 times a day, 7 days a week, as it flowed through the lean manufacturing process. Each move required 2 technicians to leave their regular jobs to assist 2 other technicians in moving a system, creating productivity and workflow disruptions, and increasing the risk of error and injuries.

Powered pallet jacks were in use in 10% of the manufacturing lines, but they did not perform as intended, and they lacked safety features the company wanted. The engineers established design goals for the new system based on safety, ergonomics principles, functionality, and low push force requirements. They then began scientifically testing the push/pull forces for prototype systems to find an optimal solution.

Their ergonomics approach proved to be a huge success. The new system involves several dolly designs with ergonomically designed low resistance casters, and a modified electric pallet jack called a "tugger." Jon Paulsen, Ergonomics Engineering Supervisor, explains: "We tested six dolly and caster designs and learned that not all casters are equal. After four design iterations, we arrived at the new dolly and tugger design based on ergonomics, safety, usability on all system types and configurations, product damage avoidance, and cost. In the end, we were able to reduce the number of technicians needed to push a system by 50%, leaving the others to attend to their designated work without disruption. When pushing the systems in a straight line, we were able to reduce the push force, distributed between two employees, to 60 lbs. and thus avoid using the tugger in many areas of our manufacturing lines. Clean room floor space is very expensive, so we wanted to use as little space as possible. A 60 lb. push force for a 7,000 lb. piece of equipment is an incredible achievement. We are very pleased with the advances in caster technology that allowed us to achieve this push force. Our time studies show that we increased productivity by almost 400% in terms of man-hours. Plus, there haven't been any injuries related to this task since we instituted the new system over a year ago."

A. Factors That Affect Pushing and Pulling

Figure 3 captures the essence of a pushing task – the person pushing must overcome the forces that resist motion. To generate and apply force to the equipment, she must have adequate friction/traction at her feet; she must be able to generate adequate strength; and she must apply her force to the equipment, usually through the hands. Figure 4 expands on this simple concept and specifies a number of important factors that define how much resistance wheeled equipment will produce and how much force a person will be able to generate and apply.

Figure 3. When people push wheeled equipment, they generate force and transmit that force through a contact point with the equipment. Friction at their feet must be at least equal to the resisting forces of the equipment, otherwise their feet will slip.

Figure 4. Some key factors that must be considered when designing a safe and productive pushing/pulling task, including human factors, task factors, cart and caster design, and floor and environmental conditions.

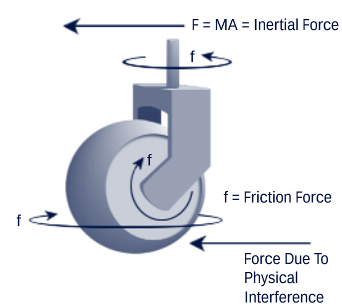
B. Rolling Resistance: Forces That Resist Movement

The forces that resist movement, generally referred to as Rolling Resistance, define how much force a person must generate and apply. Several types of forces combine to resist movement (Figure 5):

- Dynamic, or Inertial Forces
- Forces Due to Physical Interference
- Friction Forces

The force required to push/pull wheeled equipment is always greatest at the start, just before movement begins. Ergonomists refer to this force as the initial, or starting force. Fortunately, the initial forces typically last a short time and drop to the sustained force levels once the acceleration and any mechanical interference at the start of movement is overcome. Once in motion at a relatively constant speed, the force requirement is generally lower. This force is called the sustained, or rolling force. Turning forces occur when the path of travel is changed while the equipment is already in motion, or they can occur when a cart or equipment is being positioned (e.g., small motions while trying to precisely position the equipment).

Figure 5. Forces at the caster and wheel that resist movement include friction in the axle, friction at the swivel axle, and friction and physical interference at the floor-ground interface.



Dynamics, or Inertia

The initial push force is always higher than the sustained force, in part because it includes the force required to overcome inertia. Push force is directly related to the acceleration with which the force is applied. The famous 17th Century scientist Isaac Newton determined the relationship among force, acceleration, and the mass (which is directly related to the weight) of an object to be:

Force = Mass * Acceleration
$F = Ma$

The dynamic forces exist only when the equipment is being accelerated (or decelerated). Acceleration occurs at the start of a push, as the load is accelerated from a stationary position to some movement velocity; when the load is slowed, causing a change in velocity; and when the cart or equipment is turned, causing an acceleration in a new direction.

Friction at the Wheels/Casters

Whenever two surfaces are in contact, friction will resist movement between them. In “perfect” conditions, which exist primarily in theory, a laboratory, or other highly controlled environments, a hard, smooth wheel rolling on a hard, smooth surface would experience the least resistance to rolling. (Other factors, including diameter, tolerance in the round (concentricity), material resilience, and energy loss affect rolling resistance, as well.) In realistic operating environments, however, these perfect conditions rarely, if ever, exist. Using hard wheels under typical conditions will often result in higher rolling resistance, increased noise and vibration.

Friction is defined as either static (starting) or dynamic (rolling). The static forces are usually higher than the dynamic. Therefore, when considering the force a person needs to apply to a stationary piece of wheeled equipment, the initial force to create motion will almost always be higher than the force needed to sustain motion. This is because acceleration is applied, and the static friction forces must be overcome. The starting force is also affected by physical interference, which is discussed in more detail below.

In a wheel or caster system, there are three locations where friction can act to resist movement, increasing the required push forces:

1. In the axle-wheel interface;
2. In the swivel housing (for swivel casters); and
3. At the ground-wheel interface when a wheel is slid or pivoted on a surface.

By selecting well-designed casters that utilize modern design technology and materials, resistance due to friction can be kept to a minimum. Friction between the wheel and the floor is negligible, unless it occurs from pivoting the wheel on the floor surface, or from sliding the wheel across the floor perpendicular to its rolling direction.

Resistance to Rolling in the Wheel/Axle/Bearings

Typically, wheels and casters are offered with either precision bearings, which are best when sealed and therefore should be maintenance free, or bearings that require maintenance, such as cleaning and lubrication. Some wheels are offered with only a bushing and these should be avoided. Bearing technology has improved to the point that for better casters, the wheel material and diameter are actually more important than the type of bearing. However, sealed precision bearings provide the added advantage that they are maintenance free. Maintenance is often overlooked in caster selection, which can be an expensive mistake. When bearings become dirty or contaminated with debris, or the lubricant breaks down and is not refreshed through maintenance, the rolling resistance can quickly and significantly increase. If precision bearings are not chosen, a strict maintenance or inspection regime should be put in place to ensure that rolling resistance at the bearings is kept to a minimum.

Swiveling, or Turning Resistance

Three types of forces combine to resist turning: friction in the swivel housing and at the wheel-ground contact point; inertial forces due to acceleration applied in the turning direction; and any physical interference that may be present at the wheel-ground interface. When the cart is in motion, and a turn is initiated over some arcing distance, the inertial forces are restricted to how much acceleration the operator applies in the new direction. When performing fine positioning, which is often a series of stops and starts, the inertial forces may have a greater effect due to the accelerations and decelerations inherent in these motions. However, friction at the floor (or in the swivel housing for inferior or poorly maintained casters), while the wheel surface pivots on the floor, can add considerable force to a turning or positioning task.

Consider the contact area between the wheel material and the floor. A smaller diameter wheel, or a compliant wheel that "flattens" somewhat under the weight of the load, will have a larger contact area than a large diameter, or hard wheel material. The smaller the contact area, the lower the resistance as the wheel pivots in place. A compliant wheel that has a large contact area under loaded conditions is sometimes said to "stick" or "grip" the floor if it is pivoted in place.

Manufacturers design casters with an offset to reduce the force required to turn and swivel (see Figure 6a). The offset design, meaning the wheel is laterally offset from the point where the caster housing connects to the equipment, provides a horizontal lever arm between the equipment and the point where the wheel contacts the ground. Without this offset, a swivel caster would not swivel unless the equipment was moved in an arc. With the offset lever arm, a horizontal force applied to the equipment acts through the lever arm to pivot the wheel with much greater ease and with a much smaller arc of travel. When fine positioning a piece of equipment, the small travel arcs are very desirable.

Figure 6b shows an innovative caster design that eliminates the gripping effect all together. When the double wheel design pivots, the wheels roll in opposite directions and no gripping or pivoting occurs directly on the wheel surface. The twin wheel design reduces turning forces, thereby protecting the life of the caster. Also, some caster companies offer extended offset swivel designs that make positioning easier.

Figure 6a. A swivel offset helps pivot the wheel. This offset can be varied to suit the application.

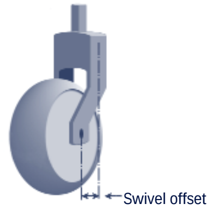
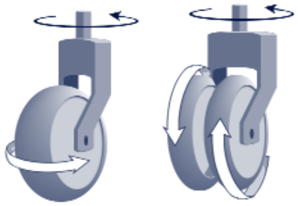


Figure 6b. Single wheel casters pivot on the wheel surface, leading to increased force due to friction and wheel surface damage. Twin wheeled casters (right) reduce friction and wheel damage by rolling when the caster is rotated.



Carts and equipment with four casters are often designed with two swivel casters and two rigid casters. In such cases, the handhold should be on the side with the swivel casters, which reduces the twisting forces and motions necessary to maneuver the cart.

Physical Interference

Physical interference (i.e., a physical barrier or interference to rolling) occurs when wheel or floor materials deform over time or when a wheel must roll over debris or an uneven surface.

"Flat Spots" and Wheel Damage

One form of mechanical interference is due to "flat spots" or other wheel irregularities. For example, if a loaded cart is left stationary for some time, the wheel or floor material may slowly deform, creating a small flat spot at the wheel-floor interface. On a smaller scale, this can also occur in the bearings. Thus, when a person begins to push the cart, she must overcome the "flat spots," as well as the initial forces due to static friction and acceleration.

Permanent flat spots and other wheel material damage can occur with "wear and tear." In particular, flat spots may develop when a non-swivel wheel is slid across a surface perpendicular to the rolling direction or when a swivel wheel is pivoted in place. Caster designers use the offset caster to reduce this effect, but when a wheel pivots in place, there will still be some gripping between the wheel and the ground, and friction can wear the material to create flat spots and reduce wheel life. Inferior wheel material or a mismatch between wheel material and expected operating conditions can result in accelerated deterioration and resultant increases in rolling resistance.

A wheel with permanent flat spots or physical damage not only has a greater resistance to rolling, but also can be very noisy and create vibration, which may damage equipment, and in severe cases, may contribute to human vibration related injury.

Uneven Surfaces, Debris, and Embedding

Rough or uneven surfaces, debris, and other contaminants can create physical barriers to rolling. When a wheel encounters such physical barriers it must roll up and over that barrier. The forces required to do this depend upon the size of the barrier relative to the diameter of the wheel. For example, a small diameter wheel encountering a small stone will experience great resistance. As the diameter of the wheel increases, the resistance will become lower and lower, until the relative difference in size is so great that the small stone is more like a grain of sand in relation to the wheel. Wheel diameter is one of the most important factors, yet it is often overlooked.

The resilience of the wheel material, or how compliant it is, is another important factor when a wheel rolls over physical barriers. If the wheel is "soft," it will deform and absorb the barrier to some extent. In this case, the wheel does not have to rise up and over the barrier, and the resistance is therefore lower. Resilient wheels also absorb shock, resulting in less vibration and quieter operation.

Another consideration is "embedding," which occurs when debris gets "stuck," or embedded on the wheel surface. Like flat spots on a wheel, embedded materials can result in increased rolling resistance, vibration, and noise. The likelihood of debris embedding in a wheel is dependent on the elasticity of the wheel material. A wheel material that does not "bounce back" is more likely to become embedded than a material that quickly reshapes to its intended form. That is, a more elastic material effectively ejects the embedded debris.

Generally, a "softer," elastic wheel material is better, unless you can be sure of a hard, clean, smooth floor. Often, there is some trade-off between wheel diameter and wheel "softness."

Sloped Surfaces

You have no doubt experienced what occurs when you push wheeled equipment up or down a slope. On flat surfaces, the resisting forces are restricted to those previously described. When a slope is encountered, the weight of the equipment also comes into play, acting either against or for the operator.

Going down usually requires no push force, because the force created by gravity overcomes the other forces acting to resist movement. In fact, as the slope increases, the operator may have to apply pulling forces so as not to lose control of the free moving equipment. Brakes are recommended for wheeled equipment that has a tendency to "run" when going down sloped surfaces.

In the same way, gravity acts against the operator when equipment is pushed up a slope. The steeper the slope, the more the equipment weight must be borne by the operator. As the slope approaches vertical, the operator is essentially bearing the entire weight of the equipment, plus any friction, physical, or dynamic forces.

Special Environments or Contaminants

Certain operating environments require specialized casters and wheel materials. For example, in flammable environments and medical facilities, static electricity is a significant safety concern, and special equipment selection is required. Clean rooms and environments where chemicals may be present also require special equipment selection, and you are encouraged to consult with experienced manufacturers and vendors in these situations.

Starting, Rolling, Turning, Stopping, and Positioning

To better understand the forces in a typical pushing/pulling task, imagine a task that requires moving a cart some distance, turning the cart around a corner, and then stopping and positioning it at the end of the route. There are four phases in this task:

- Starting or Initial Force
- Rolling or Sustained Force
- Turning Force
- Stopping or Positioning Force

Starting

To start the motion, the operator must overcome inertial forces, friction forces, and any other mechanical/physical forces that may be due to such factors as flat spots on the wheel, debris or irregularities on the floor. If a caster is turned, additional resistance must be overcome until it aligns in the direction of travel. Under typical conditions, the force to initiate movement (the starting or initial force) is always higher than the force to sustain movement.

Rolling

Once started, the operator usually does not need to apply much, if any, acceleration. Therefore, the inertial forces either go to zero or become low once moving at a relatively constant velocity. (Remember, any change in velocity means acceleration. So, if the operator tries to speed up, slow down, or turn, inertial forces will occur.) Once in motion, at a relatively constant velocity, the forces resisting movement are restricted to friction and physical interference from wheel or floor irregularities, and momentum tends to keep the equipment in motion.

Turning

Two primary forces combine when the cart is turned: inertia due to acceleration in a new direction and friction in the swivel housing and between the floor and the wheel. The cart's momentum, which is related to its mass (weight), wants to carry the cart in the direction it was traveling, so the operator must overcome that by applying higher forces in the new direction. A well-designed and maintained caster will have low frictional resistance to turning at the bearings in the caster housing, so the real friction concern is related to any pivoting at the wheel/ground interface. Swivel casters are designed with an offset for this very purpose, as discussed previously. Depending on the weight of the cart, the acceleration at which it is turned, and the friction at the casters, the turning forces can be significant. The result is that an operator will need to apply new forces in new directions, often in asymmetric body postures and muscle exertions, which can increase the likelihood of injury.

Stopping/Positioning

If, at the end of the travel route, the operator can simply release the cart and let it roll to a stop on its own, there is no need to apply any force. However, if it must be stopped or positioned in a specific place, the forces can be significant and multidirectional in the case of positioning. Such multidirectional forces can expose the operator to potentially hazardous postures and muscle exertions. Stopping, in terms of inertial forces, is the same as starting, but additional force is applied to decelerate, rather than accelerate. Positioning is a series of starting, stopping, and turning forces, which are typically the highest force conditions required in a pushing task.

C. Factors That Affect a Person's Ability to Push or Pull

So far, this paper has focused on the forces that combine to resist movement. It is the operator – a person – that must generate and apply enough force to overcome the resistance. Additionally, there must be enough traction, or friction at the feet for the person to successfully apply the push/pull force without slipping. We will now focus on the factors that affect a person's ability to safely and effectively complete a pushing and pulling task.

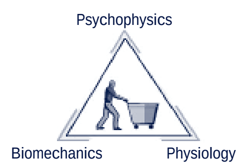
Ergonomists seek to design work, tools, equipment, etc., to fit as many people as possible in the expected user population. The rule that "one size does not fit all" becomes apparent in every situation.

Perhaps the most frustrating part about designing equipment for use by people is that we have very little control over the size, shape, age, physical strength, etc., of the people who will use the equipment. Certain design features can influence how people will use the equipment, but there is still much variability in who uses it and the way they use it in the real world. There are occasions when a push/pull task might be designed for one specific person. However, in most workplaces, any given task may be completed by a variety of people.

When there is little control over the size and abilities of the people in a process, ergonomists recommend designing or selecting easily adjustable equipment that each user can fine-tune for his or her particular needs and abilities. Where adjustable equipment is not feasible, ergonomists recommend designing for the reasonably expected worst-case scenario, with the goal being a design that makes the task safe and efficient for the greatest number of people in the expected user population. For pushing and pulling, it is often the required force that dictates who can and cannot perform the task, so we want to design for the lower strength capabilities in the user population. Therefore, we usually select the 5^{th}, 10^{th}, or 25^{th} percentile female as our lower strength design limit. If she can accomplish the task safely, we expect that larger and stronger people will also be able to do so.

Three primary analysis and design perspectives can be applied to determine appropriate design limits for manual material handling work: psychophysics, biomechanics, and physiological approaches (Figure 7).

Figure 7. The three primary analysis and design perspectives used by ergonomists



Biomechanics

Biomechanical research and analysis is an approach ergonomists use to establish strength, force, and posture guidelines. Biomechanical methods use posture, gender, anthropometry (body size), and push/pull forces to calculate resultant muscle force requirements and bone and joint compression forces. The calculated values are then compared to accepted limits for working populations. Biomechanical analysis methods are useful when analyzing high exertion tasks, but often do not consider the effects of the dynamics, repetition, or duration of the task or job.

Physiology

When a manual material handling job requires highly repetitive, fast paced, or forceful exertions, Physical Work Capacity (PWC) and fatigue must be considered. Each person has a unique PWC, which is a measurement of maximum aerobic capacity, or metabolic expenditure capabilities. Your PWC is affected by age (decreases with age), fitness, gender (men typically have a higher PWC than women), maximum heart rate, and the energy demands of the job (repetition, exertion levels, and duration/length of time spent performing the job). When physiological limits are exceeded, fatigue occurs, and in severe cases, a person's cardiovascular system may be stressed to the point of heart failure. This is especially important to consider if the expected user population for a physically demanding job will include older or "out of shape" people, which is a reasonable expectation when designing for the general working population.

The body also produces heat, which must be dissipated at a rate high enough that the body temperature does not rise and cause heat stress, or even death. The rate at which heat can be dissipated depends on a variety of physiological factors, and is affected by clothing, external temperatures, humidity, and air movement.

Psychophysics

The psychophysical approach has proven to be very useful when designing a new push/pull task or when analyzing an existing task. The psychophysical approach to evaluate or design manual handling tasks was pioneered by Snook, Ciriello, and their associates at the Liberty Mutual Insurance Company Research Center. These studies, conducted since 1967, culminated in an extensive published data set in 1991.

In simple terms, psychophysics is a research method that takes human perceptions into account. Liberty Mutual successfully applied the method to lifting/lowering tasks, carrying tasks, and pushing/pulling tasks. For pushing and pulling, they developed a set of guidelines based on these key factors:

- Type of Task
- Type of Force
- Gender of the Person
- Percent of the Industrial Working Population that Should be Able to Safely Perform the Push or Pull
- Distance of the Push or Pull
- Height of the Hands from the Floor When Performing the Push or Pull
- Frequency or Repetition of the Task

In "Guide to Designing a Push/Pull Task," to follow, data from the Liberty Mutual Studies will be presented that will help you identify the appropriate push/pull forces for your situation.

Handholds

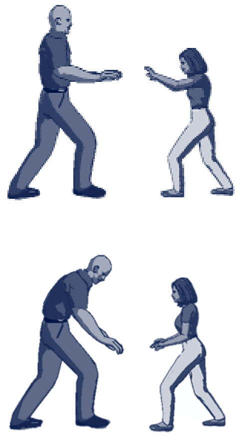
Most carts have handholds of one kind or another. Handholds are important, because they send a message to the person regarding where and how to apply force to the equipment. Some equipment may not have designated handholds, and the person therefore seeks the most convenient or mechanically advantageous method to apply force. When equipment is to be moved manually, it is advisable to incorporate designated handholds or a surface area that will provide good force application contact points for the person.

As a matter of safety, handholds should not require or encourage the person to have the hands, fingers, or arms protruding to the side of the equipment, because a crushing injury between the equipment, walls, and other equipment is very likely in such instances.

Handhold Height

Handhold height is important because it defines, in part, what posture the person will assume. Unfortunately, there is no single handle height that is "correct" for all people. Figure 8 demonstrates the effect of handhold height on posture, showing a small female and a large male reaching to the same height. A height that is appropriate for the small female may cause the large male to bend or stoop. Likewise, a handle height preferred by the tall male will cause the small female to reach up. This is significant, because the force a person is able to generate is directly related to posture.

Figure 8. Handhold height is important because it defines, in part, the posture a person will assume, and a person's ability to generate a push/pull force is directly related to posture.



An adjustable handle system is one way to accommodate people of most sizes, but such adjustability may not be feasible for some applications, and few vendors offer adjustable features at the time of this writing. Another approach is a handhold system that offers continuous vertical handles that can be grasped anywhere along their length or a series of handholds at different heights.

Handhold Width

Operators should be able to contact handholds as near as safely possible to the outer edge of a cart, avoiding crushing injuries, but providing ample leverage for turning and positioning.

Handhold Type

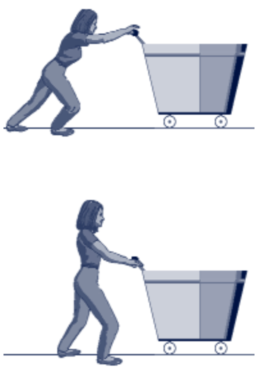
Handle type can significantly influence the amount of force a person can apply through the hands. Ergonomists refer to the hand-equipment interface as "coupling," and research shows that poor coupling can lead to as much as a 65% decrease in push-pull force capabilities.

In general, a handle should be shaped so that it does not concentrate pressure on any specific part of the hand (i.e., it should not have sharp edges, pronounced ridges, etc.). The person should be able to grip the handle with a power grip, meaning the fingers and the palm of the hand should be in contact with the handle. The fingers should not overlap, and the handle should be wide enough to accommodate the entire hand.

A handhold that accommodates a grip (i.e., the fingers wrap around it) is required for pulling tasks. However, pushing capabilities are comparable with or without handles, as long as there is a good surface for stable hand-equipment coupling.

Body Posture

Figure 9. When significant force must be applied by the operator, she will assume a posture that maximizes her ability to generate high forces using her large muscle groups, and extending her feet behind her center of gravity, requiring high foot-floor friction forces (top). At lower forces, the operator will stand in a more upright posture (bottom).



The human musculoskeletal system is essentially a series of mechanical levers. Each muscle begins on one bone and attaches, across a joint, to an adjacent bone. The position of the joint – the posture – defines the length and position of the muscle and lever arms. Some postures are more mechanically advantageous than others, and a person is able to produce a greater amount of force in these optimal postures than she is in an awkward posture. Also, certain muscle groups are bigger and more powerful than others, and a person is able to generate the largest forces when these muscle groups are used, especially when they are used in their optimal exertion postures. This is evident when you see a person pushing an object that requires excessive force; she will attempt to align her body with the horizontal force requirement, such as the posture pictured in Figure 9. In such a posture, the person is able to use the large muscle groups in the legs and torso. This person has the added benefit of using part of her own body weight to generate the force.

The best posture for starting a push is not necessarily the best posture for pushing once the equipment is in motion. Balance, as related to foot placement, becomes a primary factor, and the appropriate posture will become more upright in many movement situations (e.g., Figure 9.)

Foot Positioning

The posture used while pushing is defined in large part by the height of the handholds and the location of the feet. A person is able to generate the greatest push force when the feet are separated, one foot some distance ahead of the other (e.g., Figure 9.) In this posture, the rear foot, and sometimes the front foot as well, may be behind the body's center of gravity (or ahead of the body's center of gravity in the case of pulling). Thus, if the person loses her footing or handhold, a fall can occur. Forces that require this level of exertion should be avoided in pushing tasks, especially if the task is repetitive. Such high forces will also be beyond the safe performance of many workers.

Friction Forces, or "Traction" at the Feet

Friction forces at the foot/floor are one of the most important, yet often the most overlooked, factors in pushing and pulling tasks. Isaac Newton, who stated the previously discussed F=Ma relationship, also observed the physical law that for every force on a body, there is an equal and opposite reaction force. In the case of pushing, whatever force is applied to the equipment by the hands must be reacted to by an equal force at the foot/floor interface. If, for instance, you apply 30 lbs. of horizontal force to a cart handle, the friction force at your feet must be equal to 30 lbs. If the foot slips easily on the floor, meaning there is a low coefficient of friction (COF) between the shoe and the floor, the amount of force a person can apply to the equipment will be limited to the amount of friction force or traction at the feet. Furthermore, if the person has limited traction at the feet, she is unable to safely optimize her posture by leaning into the equipment (or away in the case of pulling), because her feet will begin to slip, and she may completely lose balance and fall.

Researchers have shown that a person pushing with good traction (high COF, e.g., 0.6 or more) can generate as much as 50% more force than when pushing in a poor traction (low COF, e.g., 0.3 or less) environment.

Angle of Push/Pull Force Application

The force required to move a cart or equipment is in the plane horizontal to movement. That is, for a cart being pushed on a flat surface, the most effective force application will be in the direction parallel to the floor. In an actual pushing situation, however, the person may be unable to apply her force exactly in the horizontal direction. For example, a high or low handle height may make it difficult or impossible to align her body in such a way as to apply a strong horizontal exertion. In other cases, the person will intentionally apply force to the handholds at some angle from the horizontal in order to increase her foot/floor traction. She can increase the vertical reaction force at her feet, and thus her foot/floor traction, by applying an upward-forward force at the handholds. Likewise, if she is pulling, she can increase traction by applying an upward-reward force to the handholds, resulting in an increased vertical reaction force at her feet.

Applying a downward-forward push force does not help foot traction, but it does allow her to utilize body weight to her advantage.

Length of Travel

The amount of force a person can apply is also influenced by how far the equipment must be pushed. The amount of force a person can sustain decreases as the distance traveled increases.

Frequency, or Repetition of Task

Repetition, or frequency, is typically related to the job or task cycle. For instance, if a task cycle includes pushing equipment five times every hour, then the repetition rate is 5/hour, or 0.083/minute. As repetition increases, the force a person can exert decreases, especially as the length of time (duration) of the task increases. Repetition increases metabolic demand, and also reduces the amount of time body tissues have to recover between loading.

Duration of Task

The duration of a task or job is simply the length of time it is performed. For example, if a worker pushes equipment for 8 hours a day, the duration of that pushing task is 8 hours. In this case, duration is not the duration of a single exertion, but the duration of the push/pull task in a given day.

Clearly, performing a pushing/pulling task for 8 hours a day will be more taxing than doing the same for 1 hour per day. Therefore, a person will be able to push with a higher force in a lower duration job than in a high duration job.

IV Quick Guide to Designing a Push/Pull Task

If a pushing/pulling job is to be performed manually, your primary goal is to minimize the forces required by the operator to initiate and sustain rolling, turning, and positioning. Five main topics must be considered in order to design a safe and productive push/pull task:

A. The people
B. Task design
C. Operating environment and floor conditions
D. Cart or equipment design
E. Caster and wheel design

Liberty Mutual Insurance Company has published a large set of data, commonly referred to as the “Snook Tables,” that can be used to determine the appropriate force levels for straight line pushing tasks. The entire data set, including many combinations of pushing and pulling activities for both males and females, is too extensive to reproduce here. However, a useful subset of the data is available in the Appendix.

If the task requires turning or positioning, special attention must be paid to those additional force demands. Often, a wheel and caster will perform differently when traveling in a straight line than it will when being turned. Further, the design, location and configuration of wheels and casters on the equipment can have a significant effect on the force requirements. Turning and positioning requirements must be reviewed and treated on a case-by-case basis, and wheel and caster designs should be carefully reviewed with your caster supplier. In some cases, an effective task design involves both manual pushing and pulling segments and mechanically assisted segments, as demonstrated in the case study previously discussed.

Also, where force levels cannot be reduced to acceptable levels through design and caster selection, administrative controls such as assigning two people to perform the task may be an option (although, design solutions that minimize potential hazards are always preferable to administrative approaches).

A. The People

Unless you are designing for a specific person, you will usually try to design for the widest range of people you might expect to perform the task. In most workplaces, you have little control over who will perform any given job. Even if you know the person or people that are performing it today, that can quickly change. Therefore, in most cases, the following will apply:

Design Force Requirements for the Smaller Female

A small female is likely to be able to generate the least amount of force overall and therefore represents a reasonable “worst-case.” Companies in the United States often design manual material handling tasks so that at least 75% of the female population and 99% of the male population can safely perform them. If you wish to be more conservative in your design, meaning you will protect a larger portion of the working population, you might design for 90% or more of the female population to make the job more accessible to a wider population of workers.

Match Footwear With Floor Conditions to Maximize Traction

To avoid slipping, researchers suggest a COF of 0.6 or greater.

B. Task Design

Use the Data in the Appendix to Explore the Effects of Distance Pushed, Repetition, and Duration of Task on Push Force Limits

Depending on task, equipment, and operator factors, you will find that acceptable force levels for females can range from as low as 13 lbs. to as high as 57 lbs.

C. Operating Environment

A good match between the wheel diameter, wheel material, and the rolling surface conditions is of utmost importance. The following general rules apply:

The Rougher or More Uneven the Rolling Surface, the Larger the Wheel Diameter Should Be.

Even in facilities with very smooth floors, the operator often crosses cracks, seams, expansion joints, grates, door thresholds, or other surface irregularities that can cause a small diameter wheel to stop. A larger diameter wheel will roll over such irregularities with relative ease.

The More Potential for Floor Debris, the Larger the Wheel Diameter Should Be

Debris on the rolling surface is much the same as a rough or uneven surface.

Special Conditions: Oil, Grease, Chemicals, Etc.

Floor contaminants can reduce the traction between the shoes and floor, making it difficult and dangerous for the person to apply the necessary push/pull forces, and may also interfere with caster maintenance and function. Consult a qualified caster supplier to match wheels and casters to your conditions.

Special Environments: Special Floor Coatings, Dust, High Moisture or Wash Down, Extreme Temperatures, Etc.

In some industries, carts and equipment must be washed regularly, and the casters must therefore be able to withstand this without detriment to their performance. Consult a qualified caster supplier to match wheels and casters to your conditions.

The Path of Travel Should Be Free of Obstacles, and the Operator Should have Clear Visibility in the Direction of Travel

Implement Effective Floor Inspection and Maintenance Procedures

Floor maintenance and housekeeping can have a dramatic effect on the forces experienced by the operator, the stability of the load, the life of the equipment, etc.

D. Cart or Equipment Design

Optimally, each person should be able to select their own point of contact, either through an adjustable handle system, or a continuous handle system that may be grasped at the height of choice. The following general rules apply:

For Pushing, Handhold Height Should Be Between Elbow and Hip Height

Since elbow and hip heights vary from person to person, there is no single recommended handhold height for pushing. If an adjustable height horizontal handle or continuous vertical handles are supplied, a range of approximately 29 in. to 47 in. will accommodate about 90% of the American working population.

For Pulling, Handhold Height Should Be Between Hip Height and Knee Height, and the Handhold May Need to Be Offset From the Equipment to Ensure Adequate Foot Clearance

Since hip and knee heights vary from person to person, there is no single recommended handhold height for pulling. If an adjustable height horizontal handle or continuous vertical handles are supplied, a range of approximately 18 in. to 39 in. will accommodate about 90% of the American working population.

The Loaded Cart or Equipment Should Be Stable

An unstable load can fall and injure people, and damage equipment and product. Load Instability can also increase the amount of required force, as the operator attempts to control the load. Further, if the load begins to fall, the person may attempt to catch it, resulting in sudden exposure to high forces, a common cause of injury.

Handholds Should Not Extend Beyond the Sides of Equipment

Extending body parts beyond the side of the equipment exposes them to crushing injuries.

A Handle is Required for Effective Pulling, But Not Always for Pushing

For pulling, the best grip is a power grip (using the palm, fingers and thumb). The fingers should not overlap, and the handle should be wide enough to accommodate the entire hand. For a cylindrical handle, this equates to about a 1.5 in. to 2.0 in. diameter (3.8 cm. to 5.1 cm.), and at least 5 inches in length to accommodate the width of the hand. Pushing can be performed with such a handle, or the person can apply force to a flat surface, as long as the coupling is good and the hands do not slip or contact edges, sharp protrusions or other pressure points. For most applications, a designated handhold is advisable.

E. Caster and Wheel Selection

Selecting the right caster and wheel design can be the most critical part of your manual push/pull task design, because reducing the rolling and turning forces reduces the forces that the person must apply. There are numerous casters on the market, and a competent supplier can and should assist you in selecting the right design for your specific application. Important goals include:

Understand the Specific Task, Operating Conditions, Environment, and the People that will be Performing the Work Before Beginning Caster Selection

Do your homework before talking to vendors.

Match Wheel Material and Diameter with Floor Surface Conditions

This may involve a trade-off between wheel material characteristics and wheel diameter.

Match Weight of Loaded Equipment with Load Ratings for Specific Casters

A general rule is that each caster should be able to withstand at least 1/3 of the total load weight by itself.

Locate Swivel Casters Under the Handholds

Often a cart will have two swivel casters and two rigid casters. For such designs, the swivel casters should be located on the same side of the cart as the handholds.

Brakes May Be Needed if Heavy Loads Will Be Moved On Sloped Surfaces

Test Potential Wheels and Casters Under Actual Operating Conditions

Remember, your goal is to match the horizontal force requirements with the force levels you determined using the data in the Appendix. For best results, test in actual operating conditions using a push-pull force gauge to measure initial (starting), sustained (rolling), and turning forces.

A Mix of Manual and Assisted Pushing and Pulling May Be Needed in Some Situations

Sometimes one or more people can perform parts of an equipment movement task, but other parts of the same task may require powered assistance due to elevated force requirements (e.g., going up or down a slope).

V | Conclusion

This paper focuses on some of the ergonomics issues involved with manual pushing or pulling activities. Ergonomics is an applied science that is used to improve human performance. Companies can expect to improve bottom-line measures in productivity, quality, health and safety, and other product and process areas by applying ergonomics principles. By studying a task or job in detail, and carefully matching equipment and people with those demands, surprisingly heavy loads and equipment can be manually moved, safely and efficiently. In some cases, depending on required task factors such as repetition, distance traveled, force requirements, and handhold locations, a combination of manual and assisted material handling can be used. This is effective where mechanical devices perform “brute force” tasks that may expose people to injury.

Understanding the task requirements, operating environment and conditions, and the people that will perform the work when selecting carts, casters and wheels will pay off.

Andres, R.O., Chaffin, D.B., and Garg, A., (1983), "Volitional Postures During Maximal Push/Pull Exertions in the Sagittal Plane," Human Factors, Vol. 25, pp. 541-550.

Ayoub, M.M., and McDaniel, J.W., (1974), "Effect of Operator Stance and Pushing and Pulling Tasks," Transactions of American Institute of Industrial Engineers, Vol. 6, pp. 185-195.

Bacchus, C., Kumar, S., Narayan, Y., and (1995), "Symmetric and Asymmetric Two-Handed Pull-Push Strength of Young Adults," Human Factors, 37(4), pp. 854-865.

Budnick, P., (2001), "Applied Materials Leverages Ergonomics to Improve Business Bottom-Line," published on http://www.ergoweb.com.

Chaffin, D.B., Herrin, G.D., Lee, K.S., and Waiker, A.M., (1991) "Effect of handle Height on Lower Back Loading in Cart Pushing and Pulling," Applied Ergonomics, 22(2), pp. 117-123.

Chaffin, D.B., Resnick, M.L., and (1995), "An Ergonomic Evaluation of Handle Height and Load on Maximal and Submaximal Cart Pushing," Applied Ergonomics, 26(3), pp. 173-178.

Ciriello, Vincent M., and Snook, Stover H., (1991), "The design of manual handling tasks: revised tables of maximum acceptable weights and forces." Ergonomics, 34(9), 1197-1213.

Darcor Ltd., (2000), "Caster and Wheel Comparison Guide."

Ergoweb Inc., (1995 – 2001), "Liberty Mutual Acceptable Pushing/Pulling Force Tool," published in the Ergoweb Job Evaluator Toolbox™ software system, on http://www.ergoweb.com.

Ergoweb Inc., (2001), "Applied Workplace Ergonomics Training Manual," available at http://www.ergoweb.com.

Grieve, D.W., Pheasant, S.T., Rubin, T., and Thompson, S.J., (1982), "Vector Representations of Human Strength in Whole Body Exertion," Applied Ergonomics, 13(2), pp. 139-144.

Imrhan, Sheik N., (1999), "Push-Pull Force Limits," The Occupational Ergonomics Handbook, Edited by Karwowski, W. and Marras, W.S., CRC Press, pp. 407-420.

Kroemer, K.H.E., and Robinson, D.E., (1971), "Horizontal Static Forces Exerted by Men Standing in Common Working Postures on Surfaces of Various Tractions," Aerospace AMRL-TR, WPAFB, Ohio, pp. 70-114.

Mital, A., Nicholson, A.S., and Ayoub, M.M., (1993), "A Guide to Manual Materials Handling," Taylor & Francis, Washington, D.C.

The following data is a useful subset (females only) of data published in: Ciriello, V.M., and Snook, S.H., (1991), "The Design of Manual Handling Tasks: Revised Tables of Maximum Acceptable Weights and Forces." Ergonomics, 34(9), pp. 1197-1213. The entire data set, including many combinations of pushing and pulling activities for both males and females, is too extensive to reproduce here.

Table 1 summarizes initial push force data for the more conservative approach of designing for 90% of the female population. Table 2 summarizes the same for 75% of the female population. Tables 3 and 4 summarize the same for sustained (rolling) push forces. Note that some of the data is italicized, which means that exposing a person to those push conditions may exceed her physiological capabilities if carried out over an 8-hour or more work day, which can result in fatigue, or even cardiovascular failure.

Vertical distance from floor to hands	Horizontal Distance Traveled																		
	2.1 m					15.2 m					45.7 m					61 m			
	Frequency					Frequency					Frequency					Frequency			
	6 s	12 s	1 m	5 m	8 h	25 s	1 m	2 m	5 m	8 h	1 m	2 m	5 m	30 m	8 h	2 m	5 m	30 m	8 h
57 cm	11	12	14	16	18	9	12	12	13	15	11	12	12	13	15	10	11	12	13
89 cm	14	15	17	20	22	11	14	14	16	17	12	14	15	16	18	12	13	14	16
135 cm	14	15	17	20	22	12	14	14	15	17	12	13	14	15	17	12	13	14	15

Table 1. Initial push forces that should be acceptable for 90 percent of all female workers, and therefore most males, as well. All force values are in kg (multiply value by 2.2 to convert to lb).

Vertical distance from floor to hands	Horizontal Distance Traveled																		
	2.1 m					15.2 m					45.7 m					61 m			
	Frequency					Frequency					Frequency					Frequency			
	6 s	12 s	1 m	5 m	8 h	25 s	1 m	2 m	5 m	8 h	1 m	2 m	5 m	30 m	8 h	2 m	5 m	30 m	8 h
57 cm	14	15	17	19	21	11	14	15	16	18	13	14	15	16	18	12	13	14	16
89 cm	17	18	21	24	27	14	17	17	19	21	15	16	18	19	21	15	16	17	19
135 cm	17	18	21	24	27	15	17	17	19	21	15	16	17	19	21	14	15	17	19

Table 2. Initial push forces that should be acceptable for 75 percent of all female workers, and therefore most males, as well. All force values are in kg (multiply value by 2.2 to convert to lb).

Vertical distance from floor to hands	Horizontal Distance Traveled																		
	2.1 m					15.2 m					45.7 m					61 m			
	Frequency					Frequency					Frequency					Frequency			
	6 s	12 s	1 m	5 m	8 h	25 s	1 m	2 m	5 m	8 h	1 m	2 m	5 m	30 m	8 h	2 m	5 m	30 m	8 h
57 cm	**5**	**6**	8	9	12	**5**	**6**	6	7	9	**5**	**5**	5	6	7	**4**	**4**	4	6
89 cm	**6**	**7**	9	10	13	**5**	**6**	7	7	10	**5**	**6**	6	6	8	**4**	**4**	5	6
135 cm	**6**	**8**	10	11	14	**5**	**6**	6	7	9	**5**	**5**	5	6	8	**4**	**4**	4	6

** Bolded values in the above table indicate conditions that exceed the 8 hour physiological criteria.*

Table 3. Sustained push forces that should be acceptable for 90 percent of all female workers, and therefore 99 percent of males, as well. All force values are in kg (multiply value by 2.2 to convert to lb).

Vertical distance from floor to hands	Horizontal Distance Traveled																		
	2.1 m					15.2 m					45.7 m					61 m			
	Frequency					Frequency					Frequency					Frequency			
	6 s	12 s	1 m	5 m	8 h	25 s	1 m	2 m	5 m	8 h	1 m	2 m	5 m	30 m	8 h	2 m	5 m	30 m	8 h
57 cm	**7**	**9**	11	13	17	**7**	**9**	9	10	13	**7**	**7**	8	8	11	**6**	**6**	6	8
89 cm	**8**	**11**	13	15	19	**7**	**9**	10	11	14	**7**	**8**	8	9	12	**6**	**6**	7	9
135 cm	**9**	**12**	14	16	21	**7**	**9**	9	10	13	**7**	**8**	8	8	11	**6**	**6**	6	9

** Bolded values in the above table indicate conditions that exceed the 8 hour physiological criteria.*

Table 4. Sustained push forces that should be acceptable for 75 percent of all female workers, and therefore most males, as well. All force values are in kg (multiply value by 2.2 to convert to lb).

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