International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
SJIF (2025): 8.036

The Effect of Lever Arm Length on Torque and Mechanical Efficiency: A Review

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Abstract: ***This review aims to investigate the influence of the lever arm length on torque amplification and mechanical efficiency by analyzing previous studies. It explores the physical principles governing lever systems, including torque, mechanical advantage, energy efficiency, the equations governing these concepts, and their applications in mechanical engineering and biomechanics. It also outlines practical design considerations, the limitations caused by friction and structural deformations as well as recent advances in computational optimization.***

Keywords: levers, lever arm length, torque, mechanical efficiency, mechanical advantage, biomechanics, force amplification

1. Introduction

Levers are among the oldest machines invented to amplify and enhance mechanical efficiency. They are widely applied in engineering, construction, manufacturing, transportation, and other applications where they transform a small applied force to a large output to perform useful work. They work by rotating a pivot, called a fulcrum, to create an output force (torque) that is proportional to the input force and lever arm length (the distance between the input force and the fulcrum) [1]. As the length of the lever arm increases, so does the generated torque; consequently, the length of the lever arm is an important consideration in designing mechanical systems.

A lever's mechanical advantage depends principally on the length of its lever arm. Engineers adjust arm length to enhance mechanical advantage and minimize operator effort [2]. This concept applies to applies to all mechanical systems ranging from simple tools to complex industrial equipment and biomechanical systems. Biomechanical systems, such as the human musculoskeletal system, also rely on lever systems for to move and maintain posture when performing physical tasks [3]. Designating assistive tools, therefore, uses the principles of force amplification by adjusting the length of the lever arm.

The basic concepts behind levers have been studied for centuries. Recent advances in computational and material science have increased mechanical efficiency by selecting materials that minimize friction and other sources of inefficiency. Other advanced analytical techniques (e.g. finite element analysis, multibody dynamic modelling, topology optimization, computer-aided engineering (CAE), and experimental testing) have been used to test materials and designs under varying load conditions [4, 5]. These advancements have resulted in better designs for manufacturing systems, mobility aids, assistive devices, and automated systems.

This review explores the effects of a long or short lever arm on mechanical effectiveness and the production of torque from previous research. It starts with a description of how lever systems function and then explores the effect of changing the size of the lever arm on mechanical efficiency and torque. The evaluation highlights how levers are used in engineering and biomechanics, notes existing design issues, and suggests possible areas for future studies to enhance the performance and effectiveness of lever-based systems.

2. Overview of Levers

A comprises a bar pivoted about a fixed point, called a fulcrum. The effort arm transmits an input force to move a load, amplifying this input by the ratio of the relative distances of the effort arm to the load from the fulcrum [1]. According to classical mechanics, levers operate based on the rotational equilibrium principle, which states that a system remains in static equilibrium when the clockwise and counterclockwise moments acting about the fulcrum are equal [6], as shown in Figure 1.

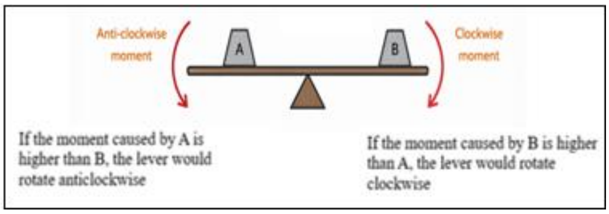

Figure 1: Moments and Rotation

The turning effect produced by a force, called torque or the moment of force, is mathematically expressed as

$$\tau = F\, r\, sin(\theta) \qquad \text{(Eq. 1)}$$

where the torque (τ) applied is directly proportional to the applied force (F) applied at some distance (r) from the fulcrum at angle (θ).

For most engineering applications, the applied force acts perpendicular to the lever arm ($\theta = 90°$). Since sin (90°) = 1, Equation (1) becomes

$$\tau = F\, r \qquad \text{(Eq.2)}$$

from Equation (2), the torque is directly proportional to the length of the lever arm. According to this equation, if the distance from the fulcrum is doubled and the applied force does not change, the torque from the applied force will also increase by a factor of two. This relationship explains the reason behind long handles on tools like wrenches and spanners to minimize the effort needed to move heavy loads...

The ability to generate higher torque with the same applied force allows a lever to amplify force and gives rise to Mechanical Advantage (MA). MA is the ratio by which a lever increases the input force, as defined below.

$$MA = \frac{F_{input}}{F_{output}} \quad \text{(Eq.3)}$$

Assuming zero friction and no energy losses, MA depends solely on the system's geometry. Rewriting Equation 3 to reflect a frictionless and fully efficient system gives Equation 4.

$$MA = \frac{L_l}{L_e} \quad \text{(Eq. 4)}$$

Where L_e is the effort arm length and L_l is the load arm length. According to Equation (4), increasing length of the effort arm relative to that of the load arm raises the mechanical advantage, and thus reduces the effort required to move a load. However, in practice, energy losses due to friction, material deformation and other factors decrease the actual mechanical advantage from its theoretical value, which makes mechanical efficiency an important consideration in lever design.

Levers can be divided into three categories depending on the position of the fulcrum, effort, and load: first, second, and third class. First-class levers have the fulcrum between the effort and the load (e.g., scissors), second-class levers have the load positioned between the fulcrum and the effort (e.g., wheelbarrows), while third-class levers have the effort positioned between the fulcrum and the load (e.g., shovels) (see Figure 2 and 3). Each setup presents unique mechanical benefits and is chosen depending on the balance needed between force amplification, speed, and range of motion.

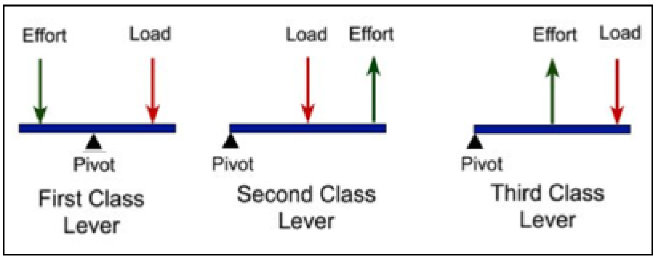

Figure 2: Types of Levers

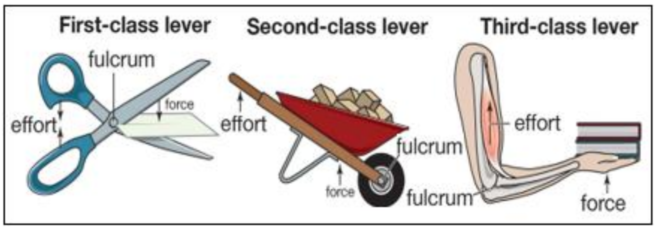

Figure 3: Examples of Levers

The Effect of Lever Arm Length on Torque

The relationship between lever arm length (r) and torque (τ) is the foundation for the design of mechanical systems, based on the equation $\tau = F.d$ $(Eq. 2)$ From the Equation (2), torque is directly proportional to the force applied and the perpendicular distance (θ) from the force to the fulcrum. A longer lever arm, therefore, has a greater turning effect for the same input force. Based on this principle, a system can generate immense mechanical force while requiring only a limited input by varying the length of the lever arm.

Torque is the rotational equivalent of linear force. Linear force causes translational motion about another axis, while torque implies motion about an axis (rotational motion). If an external force is applied to a rigid body, it can cause angular acceleration or stay in equilibrium [7]. Hence, the rotational behavior of the system depends on the magnitude of the applied force and its point of application. If the same force is applied, different lever arm lengths can produce significant different torque values. If an operator applies a force of 100 N to a wrench with a 0.20 m lever arm, the resulting torque is

$$\tau = Fr = (100)(0.20) = 20N \cdot m$$

Increasing the handle length to 0.40 m while maintaining the same applied force produces

$$\tau = (100)(0.40) = 40N \cdot m$$

Doubling the lever arm length, based on this equation, increases the torque two-fold without increasing the input force, as shown in Figure 4.

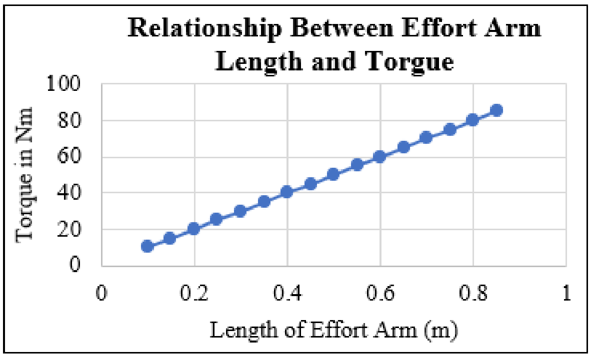

Figure 4: Relationship Between Handle Length and Torque

As this simple example illustrates, tools with longer handles are more efficient in loosening bolts or hoisting heavy items. Conversely, if the lever arm is shorter, the torque will also be reduced, and the operator will need to exert more force to obtain the same mechanical.

Although increasing the length of lever arms boosts torque, other factors limit its applicability in practice. Longer levers require more materials and increase the system weight as well as the manufacturing costs. Longer arms also experience larger bending moments and structural deflections, especially when subjected to heavy loads, hence requiring stiffer materials or reinforced cross-sections. Longer levers can also make systems difficult to operate and can take up valuable space needed to accommodate users. They can also cause instability when switching from fast to slow speed. Determining the appropriate lever arm length requires balancing torque, structural integrity, ergonomics, and economics (costs).

With the development of computational models, engineers can analyze these trade-offs more accurately. Finite element analysis (FEA), multibody dynamics, and computer-aided engineering (CAE) simulations enable designers to estimate-stress distribution, deformation and torque-transmission before manufacturing physical prototypes. These analytical tools have enhanced the optimization of the lever-based mechanisms found in industrial machinery, robot manipulators, aerospace mechanisms and medicine and health technology. Advanced optimization techniques also allow designers to calculate lever geometries that maximize torque generation while reducing material usage and minimizing mechanical losses.

Lever Arm Length and Mechanical Efficiency

Mechanical efficiency indicates the effectiveness of a lever system in converting the input force into useful work. An ideal lever is assumed to operate without energy loss (no friction, material deformation, bearing resistance, and other causes of energy loss). However, while torque increases in proportion to the lever arm length, energy losses from friction and other sources of mechanical resistance limit this gain. In practice, mechanical efficiency (η), expressed as the ratio of useful output work to the total input, is expressed as follows.

$$\eta = \frac{W_{output}}{W_{input}} \times 100\% \quad \text{(Eq.4)}$$

where η is the mechanical efficiency, W_{output} is the useful work performed by the machine, and W_{input} is the work supplied by the operator or power source. No machine can achieve perfect (100%) efficiency because part of the input energy is lost through friction, heat generation, vibration, and elastic deformation.

Lever arm length is a critical factor in mechanical efficiency because it can change the amount of force needed to do useful work. Based on Equation (2), increasing the length of the effort arm generates the same torque using the same input force, and since lower operating forces lead to lower contact pressures under the bearings, pivots and support surfaces, the tools have lower friction and less mechanical strain. For this reason, manual tools with long handles are often viewed as more efficient than their shorter counterparts because they require less physical effort and experience less wear from excessive input force.

Long lever arms deliver more torque but suffer from mechanical constraints. They have higher bending moments and may experience elastic deformation, especially when subjected to high loads. This deformation also absorbs some of the energy, thereby reducing the force delivered to the load. Longer levers also increase the rotational inertia based on Newton's Second Law of Rotation, as shown in Equation 5.

$$\tau = I\alpha \quad \text{(Eq. 5)}$$

I is the mass moment of inertia (kg·m²), and α is the angular acceleration in rad/s². Rotational inertial in Equation 5 reduces responsiveness during rapid or repetitive movements. Figure 5 illustrates the theoretical relationship between mass moments of inertia and angular acceleration derived from Newton's Second Law of Rotation ($\tau = I\alpha$).

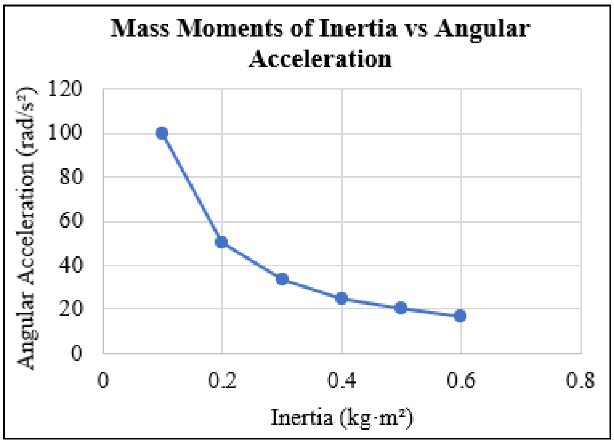

Figure 5: Mass Moments of Inertia vs Angular Acceleration

From figure 4, there is an inverse relationship between rotational inertia and angular acceleration; systems with greater inertia, therefore, require more torque to achieve the same rotational acceleration and respond slowly to changes in motion. This relationship implies that longer levers may reduce performance and require more torque.

For levers with mass distributed farther from the fulcrum, the mass moment of inertia increases based on Eq. 6 [1].

$$I = \frac{1}{3}mL^2 \quad \text{(Eq. 6)}$$

Substituting Equation 6 into Newton's Second Law gives Equation 7.

$$\alpha = \frac{3\tau}{mL^2} \quad \text{(Eq. 7).}$$

From Equation 7, the angular acceleration decreases with the square of the lever length for a constant lever mass and applied torque, resulting in slower rotational responses, as shown in Figure 6.

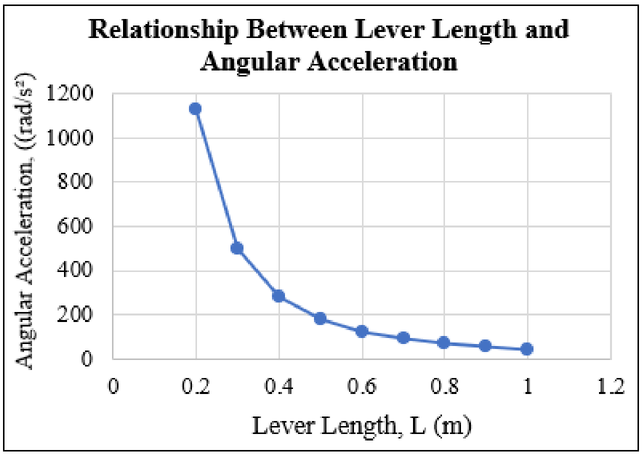

Figure 6: Relationship Between Lever Length and Angular Acceleration

Angular acceleration decreases from 1125.00 rad/s² at a lever length of 0.20 m to 55.56 rad/s² at 0.90 m, meaning that increasing the lever length also increases the mass moment of inertia, which reduces the system's ability to accelerate rotationally. The merits of higher torque, therefore, should be balanced against considerations such as structural rigidity and mass.

Friction at the fulcrum also determines the system's mechanical efficiency. Given Equation 4, $\eta = \frac{W_{input}}{W_{output}} \times 100\%$, some energy is lost to friction, represented in Equation 8 as follows.

$$\eta = \frac{W_{output - }W_{loss}}{W_{input}} \times 100\% \quad \text{(Eq.8)}$$

Expressed in terms of rotational work, i. e., torque τ and angular displacement θ, Equation 8 becomes the following.

$$\tau_{\text{applied}}\theta = \tau_{\text{load}}\theta + \tau_{\text{friction}}\theta \quad \text{(Eq. 9)}$$

If the bearings are worn or the system is poorly lubricated, the energy losses increase for any lever action. Therefore, engineering practice does not focus solely on the lever arm length; it also focuses on choice of bearings, materials, lubrication, and manufacturing tolerances to optimize performance.

Lever systems have been optimized further with recent advances in computational engineering. With finite element analyses, multibody dynamic analyses, and topology optimizations, engineers can design and test a combination of lever geometries, material characteristics, load conditions, and friction before making prototypes [8]. These tools have led to the development of lighter, stronger, and more energy-efficient mechanisms for various applications.

Engineering and Biomechanical Applications

The principles of lever arm length, torque, and mechanical efficiency have been applied to a wide range of mechanical engineering, industrial, manufacturing, and biomechanical applications. The fundamental principles remain the same, but the objectives of lever design vary based on the intended use. In mechanical engineering, levers are used mainly to increase the amount of force being transferred, boost efficiency, and reduce energy use. Biological systems tend to focus more on speed, accuracy, and range of motion performance than on achieving maximum mechanical advantage.

One of the most common engineering applications of levers is in hand-operated tools, including spanners, wrenches, crowbars, bolt cutters, and pliers. The tools use longer arms for greater torque using a smaller application force. For instance, the longer the handle length of a wrench, the easier it will be to remove a bolt that is hard to turn with a shorter handle. Likewise, crowbars have a long effort arm and a short load arm, allowing the user to lift a heavy object with much less effort. These applications show how Equation (2) can be applied in practice: As the lever arm increases, the turning moment on the load increases.

Lever principles are also crucial in industrial machinery. They are used in construction equipment, hydraulic presses, lifting systems, excavators and material handling systems to efficiently transfer force while keeping the structure stable. For manufacturing operations, lever-operated fixtures and clamping devices enhance accuracy, giving operators strong clamping force without much effort. Articulated joints also use lever mechanisms for robotic manipulators, with an optimized body configuration to guarantee positioning accuracy and reduce the power consumption of the actuators, while also allowing an optimized transmission of torque. Improved computational optimization techniques are increasingly used today to define the optimum leverages in modern robotic systems for specific operations.

Most of the human limb's function as third class levers, with muscular force applied between the fulcrum and the external load, as illustrated in Figure 7.

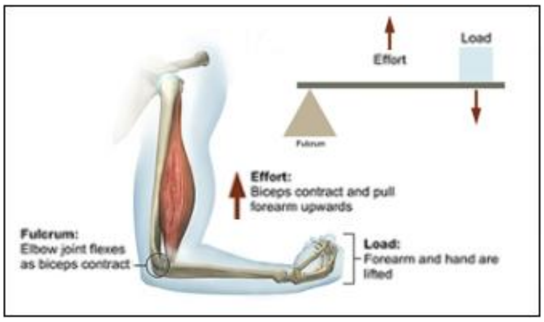

Figure 7: Human Arm as a Third-Class Lever.

Adapted from Visible Body, 2026 [11].

This setup gives it relatively low mechanical advantage, but facilitates fast limb movements, supports high angular velocity, and enables a wide range of motion [9]. These qualities are important in activities that demand speed and accuracy, such as for walking, running, throwing, and handling objects. In contrast, in a second-class lever, such as standing on the toes, the load is placed between the fulcrum and the effort so that larger forces are created when jumping or lifting body weight.

The study of lever arm length and mechanical performance also has facilitated improvements in rehabilitation engineering, prosthetic design, sports biomechanics, and ergonomics. When designing a lever mechanism, engineers strive to keep the load and resistance at the joints to a minimum and prevent undesirable movement to limit chances of developing musculoskeletal injuries [10]. Ergonomic tool design, for example, aims at developing proper handle size to reduce operator fatigue while at the same time increasing productivity. The study of lever-based systems is evolving rapidly with improvements in computational modelling and biomechanical analysis, which will lead to more efficient and lightweight engineering and healthcare applications.

3. Current Challenges and Future Research

Although lever systems have been implemented in many engineering and biomechanics applications, some difficulties exist in optimization their performances under practical operating conditions. The vast majority of theoretical analyses employ ideal rigid bodies, ignore frictional forces and energy losses due to material deformation or other causes. In practice, however, bearing friction, elastic deformation, wear and fatigue, manufacturing tolerances, and dynamic loading affect these systems, meaning that the accuracy of theoretical predictions remains less precise. Thus, the relationship between lever arm length and torque production is often more complex than the simplified analytical models can describe.

Recent advances in computational engineering have created new opportunities for improving lever design. Stress distribution analysis, multibody modelling, topology optimization and artificial intelligence are increasingly being applied to analyses stress distribution and predict stress and performance under complex loading conditions. Additive Manufacturing (AM) has also enabled the creation of lightweight lever structures with enhanced stiffness-to-weight ratios that were not achievable using conventional manufacturing methods...

More research is needed to combine advanced materials and smart sensing in lever systems. These advances could create more efficient mechanical systems with lower structural mass and adaptable mechanisms that can change their behavior to match the varying demands of their operating environments in industrial, robotic and biomechanical contexts.

4. Conclusion

Lever arm length is one of the basic variables that affects torque production and mechanical efficiency of a lever system. The reviewed literature confirms that, in theory, extending the lever arm increases torque and decreases the input force needed to perform mechanical work, but limits to actual performance exist due to friction forces, material deformation, and structural limits. These principles form the basis for many mechanical engineering and biomechanics applications. Potential future enhancements to the efficiency and performance of any future systems utilizing levers may draw on additional progress in computational modelling, material technologies, and optimization techniques.

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