

Fifth Edition

ATLAS of ORTHOSES and ASSISTIVE DEVICES

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Basics

Joseph B. Webster

The rehabilitation of persons with disabling illnesses or injuries is best accomplished through an interdisciplinary team approach and a treatment plan that includes a host of intervention modalities. The goal of this approach is to assist the person with the disabling condition to achieve their highest level of functional independence and community integration. The prescription, fabrication, and fitting of orthoses and assistive devices is often an important component of the treatment regimen. Successful prescription of an orthosis or assistive device begins with a solid understanding of underlying physiologic concepts as well as an appreciation of biomechanical and kinesiology principles. This knowledge, in combination with the technical skills that are required in the fabrication and fitting of these devices, leads to successful patient outcomes.

Section I of this text is designed to provide the reader with a solid foundation of knowledge that will be instrumental as the reader applies this information in the provision of orthoses and assistive devices for the specific conditions covered in the subsequent sections of the text. Each chapter in Section 1 provides a sufficient level of detail to stand alone as a valuable resource for the reader, but these chapters also provide solid reference lists for those who have a desire to explore these chapter topics in more detail.

The development of the prescription for an orthosis or assistive device is a crucial early task in the rehabilitation process. Chapter 1 provides comprehensive coverage of this topic and emphasizes the importance of a clear, concise, and complete prescription in order to assure that the orthosis or assistive device is able to achieve its desired goal. The chapter also covers the interdisciplinary communication required for successful prescription development and the primary responsibilities of each team member.

Chapters 2 and 3 cover the topics of material science and principles of fabrication in a detailed, yet understandable fashion. While thorough comprehension of all of the information covered in these chapters may not be required in every situation, the content will be valuable for both new practitioners and well as for those who may need to refresh their knowledge base to address a unique challenge or prior to implementation of a new process.

Chapter 4, which covers the fundamental aspects of normal and pathologic gait concludes Section 1. The key points covered in chapter 4 include the lower extremity joint interactions that are required for normal gait. The chapter also emphasizes the importance of understanding underlying biomechanical principles and applying observational gait analysis skills in the evaluation of pathologic gait patterns.

Orthotic Prescription

Ann Yamane

KEY POINTS

- A prescription for an orthosis communicates the type of device recommended to meet the biomechanical needs of the patient to improve function and promote participation in life activities.
- An appropriate orthotic prescription and treatment plan is generated based on knowledge of the patient's disease process along with information from a comprehensive history, physical examination, and integration of patient-related and environmental factors.
- Optimally, the prescription for an orthosis is determined with input from members of the health care team and patient, incorporating meaningful shared rehabilitation goals that use patient-centered and interdisciplinary team approaches.
- An effective prescription for an orthosis summarizes the medical and functional issues related to the patient, details the biomechanical functions desired, and specifies key technical attributes of the desired orthosis.

The prescription for an orthosis is an essential part of the larger process of rehabilitation to improve patient function and promote participation in life activities. Each member of the interdisciplinary team offers expertise that allows the team to work collaboratively with the patient to identify goals for orthotic intervention and shared rehabilitation goals.

An effective interdisciplinary approach fosters communication by involving all team members throughout the treatment process. A collaborative clinical environment allows team members the opportunity to clarify their clinical recommendations and educate other team members on their areas of expertise. Because of current health care policy and financial demands, this interdisciplinary approach may be possible in the acute setting but is typically challenging to achieve in outpatient settings. This lack of face-to-face communication requires the use of detailed documentation notes by the physician and others to convey the assessment findings and clinical reasoning.

Formulation of the orthotic prescription begins with the physician's medical evaluation of the patient, identification of the pathology and associated functional impairments, and prognosis. The assessment of the individual consists of a history that includes problems noted by the patient, prior interventions, and patient expectations and goals. The identification of patient-related and environmental factors as outlined by the World Health Organization's conceptual framework, the International Classification of Functioning, Disability, and Health (also known as the ICF) provides insight into how an individual functions in daily life. This context is key to informing the orthotic treatment plan.⁶

Determining the appropriate orthotic prescription is grounded in the biomechanical needs of the patient as identified through a physical evaluation that includes manual muscle testing (MMT), range-of-motion (ROM) testing, and sensory testing. Through the integration of the biomechanical needs and the personal and environmental factors of the individual, the optimal orthosis design is identified. Although the actual prescription for an orthosis communicates the type of device recommended to meet the biomechanical and functional needs of the patient, the physician's clinic documentation note contains the necessary information justifying the (1) need for a custom-fabricated orthosis

rather than a custom-fitted orthosis, (2) need for long-term use of the orthosis, and (3) planes of static and dynamic control necessary at each joint (sagittal, coronal, transverse).³

In addition, the physician considers additional referrals necessary to support the comprehensive orthotic treatment plan. This may include supporting therapies, medications, surgeries, or injections to improve the underlying condition before provision of an orthosis or to improve the outcomes of the intervention. For example, an individual with a knee flexion contracture and quadriceps weakness may be referred to physical therapy in an attempt to reduce the contracture before orthotic intervention. Reducing the knee flexion contracture will improve the effective use of a ground-reaction ankle-foot orthosis (AFO) by increasing the external knee extension moment created by the AFO from midstance to terminal stance.

The interdisciplinary team is most effective when team members work cooperatively, sharing perspectives and expertise and effecting a blend of the physician's medical knowledge; the orthotist's understanding of biomechanics, design, and material options; and the occupational and physical therapists' evaluation of functional abilities, education, and therapy to improve function.

Follow-up is crucial to assess the functional outcome and success of the orthotic treatment plan in meeting the patient's goals and the patient-centered rehabilitation team goals. Functional outcomes may be patient reported or performance based to assess improved quality of life, mobility, self-care, or other constructs of value specific to each individual. The Activities-Specific Balance Confidence (ABC) Scale⁴ is an example of a self-report measure used to assess an individual's level of confidence while involved in specific activities such as walking up or down stairs, in crowds, or on icy sidewalks. The Timed Up and Go (TUG)⁵ is a commonly used performance measure assessing balance, functional mobility, gait, and potential risk for falls. The routine integration of outcome measures into the orthotic treatment plan has the potential to provide increased knowledge regarding the success of the orthotic prescription in achieving the desired improvement in patient function and increased participation in life activities.



Figure 1.1 Ankle-foot orthosis (AFO).

TERMINOLOGY

An *orthosis* or *orthotic device* is an appliance applied to the body to stabilize or immobilize a body part, improve alignment, prevent deformities, protect against injury, or assist with motion or function. The term *orthotics* refers to the science and practice of assessment, fabrication, fitting, and adjusting of an orthosis.

Orthoses are described by the standards agreed upon by the International Organization for Standardization (ISO), an independent, nongovernmental organization with global representation on each technical committee.² All orthoses should be designated using ISO acronyms according to the joints or body segments involved, such as AFO for ankle-foot orthosis (Fig. 1.1) or WHO for wrist-hand orthosis (Fig. 1.2). To generate an appropriate prescription, it is crucial to use the accepted terminology.

The prescription specifies whether the orthosis is (1) prefabricated and off-the-shelf, (2) prefabricated and custom fitted, or (3) custom fabricated. A prefabricated orthosis is considered off-the-shelf if specialized training is not required to complete “minimal self-adjustments” at the time of fitting (e.g., strap and closure adjustment). A prefabricated orthosis requiring substantial modifications at the time of fitting by a qualified practitioner is considered custom fitted. A custom-fabricated orthosis is made for a specific individual from a positive model of the person obtained through casting, measurements, tracing, or an image.¹

Inclusion of specific biomechanical characteristics describing the orthosis is essential. Examples of these features include design characteristics regarding materials (e.g., thermoplastic, carbon), knee joints (e.g., drop locks, free knee, bale lock), and biomechanical controls at the ankle joint (dorsiflexion or plantarflexion assistance or resistance) (Fig. 1.3).

Ankle Joint Controls and Their Function

Other general descriptive terms, such as static, dynamic, and progressive, provide clarification of the goals for the orthosis (Table 1.1). The term



Figure 1.2 Wrist-hand orthosis (WHO).



Figure 1.3 Double adjustable ankle joint (DAAJ).

TABLE 1.1 Ankle Joint Controls and Their Function

Angle Joint Control	Function
Free motion	Allows free range of motion in the sagittal plane while controlling coronal plane motion
Fixed position	Fixed position in the sagittal plane
Limited motion	Allows controlled sagittal plane range of motion
Plantarflexion stop	Compensates for dorsiflexion weakness by limiting plantarflexion range of motion
Dorsiflexion assist	Compensates for dorsiflexion weakness by assisting dorsiflexion range of motion
Dorsiflexion stop	Compensates for plantarflexion weakness by limiting dorsiflexion range of motion from midstance to terminal stance

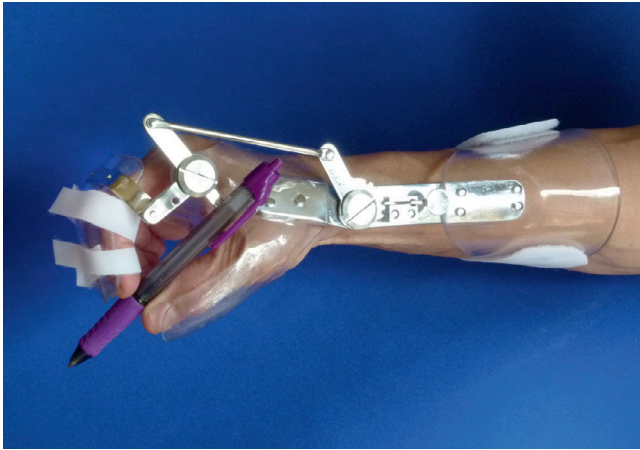


Figure 1.4 Wrist-driven wrist-hand orthosis (WDWHO).



Figure 1.5 Ankle-foot orthosis with double adjustable ankle joint (AFO with DAAJ).

static implies that there is no motion across the joint or segment involved, with stabilization as the primary goal. A static thermoplastic WHO (see Fig. 1.2) allows no motion at the wrist and may provide positioning to protect the wrist joint. A *dynamic* orthosis indicates there is motion across the joint. A wrist-driven WHO is a dynamic orthosis capturing the movement of wrist extension to provide a palmar prehension grasp (Fig. 1.4). To accommodate the reduction of a plantarflexion contracture through a stretching program, a progressive AFO design (Fig. 1.5) incorporates an adjustable ankle joint matches the individual's changing position.

EVALUATION OF THE PATIENT

A clear understanding of the patient's disease process and natural history provides the foundation to generate an appropriate prescription

and comprehensive orthotic treatment plan. Key components of the history include the initial presenting problem noted by the individual, prior interventions, functional status, and patient goals and expectations.

It is important to appreciate conditions such as diabetes, visual impairments, and hand dysfunction and understand the potential effects they will have on orthotic management. For example, an individual who lacks sensation in the body part covered by the orthosis must use visual feedback to assess for skin irritation or excessive pressure.

A physical evaluation of the patient should include assessment of strength, ROM, sensation, tone, skin integrity, and presence of swelling. Additional evaluation components that may be indicated include a postural and gait evaluation and identification of the limitations experienced while undertaking activities of daily living (ADLs) and instrumental activities of daily living (iADLs).

The individual's cognitive status should be assessed to identify issues that may affect successful use of the orthosis. If assistance will be needed, assessment of the individual's social support system is necessary. For example, if the patient is unable to independently don or doff the orthosis or monitor for potential complications related to skin problems, social support systems must be in place. In the case of visual impairment, the individual will need to rely on others to complete daily skin inspections.

ORTHOTIC PRESCRIPTION

The orthotic prescription should clearly summarize the medical issues related to the patient and the specifics of the orthotic device. The medical information should be specific and directly related to the functional deficit or reason for the orthosis. For example, an individual with an incomplete spinal cord injury (SCI) may have weakness of the lower extremities, pathomechanical gait compensations, and instability while ambulating on both level terrain and uneven ground. Not only the biomechanical needs of the individual should be considered but also the personal and environmental factors that will affect use of the orthoses. As mentioned previously, the orthotic prescription includes the ISO acronym describing the orthosis and describes the material specifications (e.g., thermoplastics, metals, or carbon fiber) and the biomechanical functions and controls to be used at each joint. The ROM or limitation at each joint should be indicated clearly on the prescription. In addition, special features such as varus-valgus corrective forces and straps, flanges, and wedges should be included for complete specification of the desired design.

With the increasing availability of orthoses with sophisticated and advanced technologies, the physician assessing the patient may be uncertain of the optimal orthotic design to accomplish the desired orthotic goals. In these circumstances, it would be appropriate for the physician to refer the patient to the orthotist for consultation and evaluation. The consultation request should include information regarding medical diagnosis, prognosis, orthotic goals, and the request to "evaluate for orthotic management." In addition, instructions on the optimal method for communication to discuss the orthosis options will facilitate timely patient care. Before proceeding, a detailed prescription will have to be generated from these discussions.

A certificate of medical necessity is sometimes required to justify the provision of devices incorporating these advanced technologies. This certification letter should include a detailed explanation of the patient's condition and current functional status as well as information on the anticipated improvement in function and increased independence with use of the orthosis. The letter should clearly state the risks to the patient if the device is not supplied.

CASE SCENARIO AND ORTHOTIC PRESCRIPTION RECOMMENDATION

Case Scenario

A 34-year-old woman recently diagnosed with multiple sclerosis reports a 1-year history of progressive weakness in the left leg. She reports difficulty walking longer distances and on uneven terrain, with recurrent falls related to the left leg weakness. She relays at least three events over the last year when she noticed acute exacerbations of weakness that stabilized over the course of several weeks. The patient has not used any orthoses to date but does use a cane when ambulating outside her home for longer distances. She lives with her husband and two young children (5 and 7 years old) in a two-story house with five steps to enter from the outside. The patient is the primary caretaker for the children. Until 4 months ago she was independent and safe in ambulation and participated in tennis and golf. Her present goals are (1) safe ambulation both indoors and outdoors on uneven terrain and (2) the ability to walk longer distances (1 mile) and go on outings with her family. On examination, she is alert and oriented, with cognition intact. She has a medium frame and stature.

Upper Extremity Examination

- Normal strength, sensation, and tone bilaterally.
- Fine motor skills in both hands are intact.

Lower Extremity Examination (Table 1.2)

- Right lower extremity: Normal sensation and tone.
- Left lower extremity: Increased extensor pattern tone; impaired sensation throughout the limb; diminished protective sensation on the plantar surface of the left foot.

ROM

- Ankle passive range of motion: 5 degrees of dorsiflexion and 40 degrees of plantar flexion.

Gait Assessment

- Inadequate clearance of the left foot drop in swing phase.
- Left knee maintained in full extension throughout stance phase.
- The patient reports that her gait pattern changes depending on her overall tone on any particular day. On days when she is rested and relaxed, she can use a steppage gait pattern to clear the left foot, but on days when the tone is significantly increased she uses a stiff knee gait pattern throughout swing phase with circumduction on the left and vaulting on the right.

TABLE 1.2 Manual Muscle Testing Findings

Manual Muscle Test	Right Lower Extremity	Left Lower Extremity
Hip abductors	4/5	5/5
Hip flexors	4/5	5/5
Hip extensors	4/5	5/5
Knee flexors	4-/5	5/5
Knee extensors	4-/5	5/5
Dorsiflexors	1/5	5/5
Plantarflexors	3/5	5/5
Invertors	1/5	5/5
Evertors	1/5	5/5

5: Normal, completes full ROM against gravity, maximum resistance.

4: Good, completed full ROM against gravity, moderate resistance.

4-: Completes greater than half the available ROM against gravity, moderate resistance.

3: Fair, completes full ROM against gravity.

2: Poor, completes full ROM, gravity minimized.

1: Trace, contraction palpated.

Assessment

In this case, the disease process is progressive-type multiple sclerosis (MS), causing weakness of the left leg with inadequate clearance of the foot during swing phase of gait or an extensor pattern of movement. The history of recurrent falls is a significant safety concern for the patient. The prognosis of this type of MS indicates that further weakness or increased tone of the left leg or other extremities can be anticipated in the future.

Rationale for Orthotic Prescription and Treatment Plan Options

- *Custom AFO rationale:* The use of a custom-fabricated AFO rather than a custom-fitted AFO is indicated based on the need for (1) coronal and sagittal plane control of the foot and ankle, (2) long-term use of the orthosis, and (3) a changing clinical situation.
- *Solid-ankle thermoplastic AFO:* A solid-ankle thermoplastic AFO (Fig. 1.6) will substitute for the dorsiflexor and plantarflexor weakness and provide coronal plane control of the subtalar joint. [The knee flexion moment created at loading response may become problematic if the quadriceps strength continues to weaken.]
- *AFO with ankle joints:* An AFO with double adjustable ankle joints (see Fig. 1.5) will provide biomechanical versatility and options for changing the biomechanical controls at the ankle as the individual's needs change over time. The type of control is included on the prescription and the rationale for the biomechanical controls at the ankle are included in the clinical documentation note. [The dual-channel ankle joint allows the option of a dorsiflexion assist (spring in the posterior channel) or a plantarflexion stop (pin in the posterior channel) to provide clearance of the foot during swing phase. The use of a dorsiflexion stop (pin in the anterior channel) preventing excessive dorsiflexion from midstance to terminal stance will substitute for plantarflexion weakness and provide an external knee extension moment should the quadriceps become weaker in the future.



Figure 1.6 Solid-ankle thermoplastic ankle-foot orthosis (AFO).

Additional AFO design features:

- A varus/valgus corrective strap or modification due to the lack of adequate inversion and eversion strength.
- Material selection is influenced by personal factors such as weight, activity level, and preference.
- *Functional electrical stimulation (FES) or Neuro-prosthesis:* The consideration of a FES system will require a prescription/referral to a physical therapist and/or orthotist for an evaluation and screening to assess the appropriateness and potential effectiveness for the individual.
- *Physical therapy:* A referral to physical therapy to establish a home stretching and strengthening program, evaluation and treatment related to balance, and gait training on stairs and uneven terrain will assist in meeting the patient and rehabilitation goals.
- *Education related to skin observation:* Because of her decreased sensation, the individual must be taught to inspect the skin regularly to avoid excessive pressure and ulceration.

• *Administration of outcome assessment measures:*

1. ABC Scale to assess the individual's perceived confidence while performing ADLs while walking and standing⁴
2. TUG to assess gait and walking ability or functional mobility⁵

CONCLUSION

The responsibility of initiating the prescription for an orthosis falls on the physician, but the process of evaluating the patient, establishing orthotic and patient-centered rehabilitation goals, and ensuring the successful use of the orthosis requires critical input from all appropriate team members. Collaboration among the team members, with members of the team recognizing their unique role and expertise, will improve the functional outcome for the patient. Follow-up and long-term monitoring of the patient and use of the orthosis by all team members is essential to prevent complications and ensure the best long-term outcome.

A complete reference list can be found online at ExpertConsult.com.

Materials Science

Thomas R. Lunsford, Bill Contoyannis

KEY POINTS

- A thorough knowledge of the material science, its application, and other general principles summarized in this chapter is prerequisite to ensuring that the orthosis and assistive devices provided by practitioners will be durable, safe, and as unobtrusive as possible and will perform the required function for as long as necessary. Understanding these fundamentals enables the practitioner to assess designs; materials; and, more importantly, failures to clearly justify the decisions, practices, and techniques used in the creation of these devices.
- The practitioner must have skills and understanding regarding many materials and have the ability to apply them, often in complex combinations. Selection of the correct material for a specific device requires an understanding of the elementary principles of mechanics and materials; concepts of forces; deformation and failure of structures under load; improvement in mechanical properties by heat treatment, work (strain) hardening, and similar means; and, importantly, many of the engineering principles behind the design of structures.
- International standards for terminology should be used to describe orthoses, prostheses, wheelchairs and other devices, properties of materials, units of measure (whether imperial or metric), and the engineering principles for describing the various effects of loading on these materials.
- The practitioner must have a thorough understanding of the specific application of a device and the biomechanical forces to be applied by the device to choose the proper material or material combination and methods of fabrication. The service success of any device depends as much on the design and fabrication process as on the material itself.
- Fatigue stresses, which are the result of repeatedly applied small loads rather than application of any single large load, are generally responsible when structural failure occurs in orthoses, prostheses, and other assistive devices, thus defining the life cycle of any particular device.

Great advancements for patients requiring orthoses, prostheses, and assistive technology have occurred because of the broad range of materials that have become available to over the last century. The ability to custom fabricate devices with intricate precision has improved the fit of devices. Materials with high strength-to-weight ratios have meant the devices are lighter, and materials that flex without failure have improved the function and performance that can be achieved.

UNDERSTANDING MATERIAL SCIENCE TO MAXIMIZE PATIENT SAFETY

The fabrication of orthoses, prostheses, and other assistive devices almost always involves the use of combinations of materials. Furthermore, there is typically a combination of prefabricated and custom-made components. The nature of designing, fabricating, and fitting these devices requires compromises in the materials and components to achieve the optimal clinical outcome.

The combination of metals, plastics, leathers, composites, foams, rubber, and other materials is frequently chosen to achieve the clinical outcome first and then manipulated to achieve the engineering strength and environmental robustness that will be required.

Practitioners need to understand the science and engineering principles that underpin the materials to achieve the structural integrity required as well as the likely compromises that are made as a result. These factors will influence the clinical review process that may be

required. The understanding of the original design and fabrication along with the review over time will allow maximum safety for patients in terms of the device that has been provided.

Selection of the correct material for a given design depends partially on understanding the elementary principles of mechanics and materials; concepts of forces; deformation and failure of structures under load; improvement in mechanical properties by heat treatment, work (strain), hardening or other means; and design of structures. For example, the choices for a knee–ankle–foot orthosis (KAFO) may include several types of steel, numerous alloys of aluminium, and titanium and its alloys. Important but minor uses of other metals include copper or brass rivets and successive platings of copper, nickel, and chromium. Plastics, fabrics, rubbers, and leathers have wide indications, and composite structures (plastic matrix with reinforcing fibers) are beginning to be used. Often complex combinations of materials are used in manners that are not appropriate from the material point of view but are appropriate for the particular clinical application (Fig. 2.1). Understanding these properties not only assists with the selection, manufacture, and management of the device but extends to the management of the patient and the information that the practitioner will instill into patients. A simple example is the combination of flexible materials such as a strap and thermoplastic, using an alloy rivet.

Despite publicity for exotic materials, no single material or fabrication process is a panacea. One reason is that a single design commonly requires divergent mechanical properties (e.g., stiffness and flexibility



Figure 2.1 A transparent diagnostic socket, reinforced using preimpregnated carbon fiber. Although this is not structurally a desirable solution, it may be clinically necessary.

required in an ankle-foot orthosis [AFO] for dorsiflexion restraint and free plantar flexion). In addition, practitioners rarely are presented with situations that require only one material or with single-design situations that do not require modification, customization, or variation over time. Despite the addition of materials such as preimpregnated (prepreg) carbon fiber and 3D printing (additive manufacture), the basic material science discussed in this chapter remains unchanged. An understanding of materials assists the practitioner with the fabrication process even when using novel techniques such as additive manufacturing.

In general, understanding by the practitioner of the mechanics and strength of materials, even if intuitive, is important during the design stage. A general understanding of stresses arising from loading of structures, particularly from the bending of beams, is needed. The practitioner can then appreciate the importance of simple methods that allow controlled deformation during fitting, provide stiffness or resiliency as prescribed, and reduce breakage from impact or repeated loading. A general discussion of materials and specific theory related to design, fabrication, riveting guidelines, troubleshooting, and failure considerations follows.

Consideration should be given to the international standards of terminology that are used to describe orthotics, prosthetics, properties of materials, and units of measure (whether imperial or metric) and the engineering principles for describing the various effects of loading upon these materials. Unless they are familiar with the particular definitions of the terms used, practitioners should generally avoid using specific terminology in favor of more objective descriptive language.

IMPERIAL AND METRIC CONVERSIONS

Most of the examples provided here are presented using both imperial and metric units. Some examples will assist with the general “comparison” between imperial and metric units or, in some cases, the direct conversion between the two (if it is possible to convert between the two; for example,

with temperature, Fahrenheit cannot be simply converted to Celsius by multiplying one value by a constant).

- 1 pound (lb) = 0.45 kilograms (kg)
- 1 kilogram (kg) = 9.8 Newtons (N) of force (the same as 1 kg \times gravity, or 9.8 meters per second)
- 1 inch (in) = 0.025 meters (m) or 2.5 centimeters (cm)
- 1 meter (m) = 39.3 inches (in)
- 1 meter (m) = 100 centimeters (cm)
- 1 centimeter (cm) = 10 millimeters (mm)
- 1 pound per square inch (psi) = 6895 Pascals (Pa) (or 0.006895 megapascals [MPa; or 1 million pascals])
- 1 Pascal (Pa) = 1 Newton per square meter (N/m²)
- Stress units: pounds per square inch or megapascals (million Newtons per square meter)
- Strain units: fraction of an inch per inch or fraction of a meter per meter

Two other factors should be noted:

- Aluminum is the same material as aluminium.
- Meters are the same as metres.

STRENGTH AND STRESS

One of the practitioner’s main considerations is the strength of the material selected for fabrication of orthoses or prostheses. *Strength* is defined as the ability of a material to resist forces. When comparative studies are made of the strength of materials, the concept of stress must be introduced.

Stress relates to both the magnitude of the applied forces and the amount of the material’s internal resistance to the forces. *Stress* is defined as force per unit cross-sectional area of material and usually is expressed in pounds per square inch (imperial) or pascals or megapascals (metric). The amount of stress (σ) is computed using the equation:

$$\sigma = \frac{F}{A} \quad (2.1)$$

where F = applied force (pounds or Newtons), and A = cross-sectional area (square inches or square meters).

The same amount of force applied over different areas causes radically different stresses. For example, a 1-lb weight (about 0.5 kg or 4.9 N) is placed on a cylindrical test bar with a cross-sectional area of 1 in² (about 6.5 cm²). According to Eq. 2.1, the compressive stress σ_c in the cylindrical test bar is 1 lb/in² or about 7538 Pa (Fig. 2.2). When the same 1-lb weight is placed on a needle with a cross-sectional area of 0.001 in² (0.0065 cm²), the compressive stress σ_c in the needle is 1000 psi or 7.5 MPa (or 7,500,000 Pa) (Fig. 2.3).

A force exerted on a small area always causes more stress than the same force acting on a larger area. When a woman wears high-heeled shoes, her weight is supported by the narrow heels, which have an area of only a fraction of a square inch. With flat shoes, the same weight or force is spread over a heel with a larger cross-sectional area. The stress in the heel of the shoe is much greater when high-heeled shoes are worn, because less material is resisting the applied forces.

Similar problems are encountered in orthoses and prostheses. A child who weighs 100 lb (45 kg) wearing a weight-bearing orthosis with a 90-degree posterior stop (Fig. 2.4) can exert forces at initial contact that create stresses of thousands of pounds per square inch. If the child jumps, this can increase the forces imparted by three to five times the body weight of the child. The stress at the stop or on the rivet could be great enough to cause failure.

Tensile, Compressive, Shear, and Flexural Stresses

Materials are subject to several types of stresses depending on the way the forces are applied: tensile, compressive, shear, and flexural.

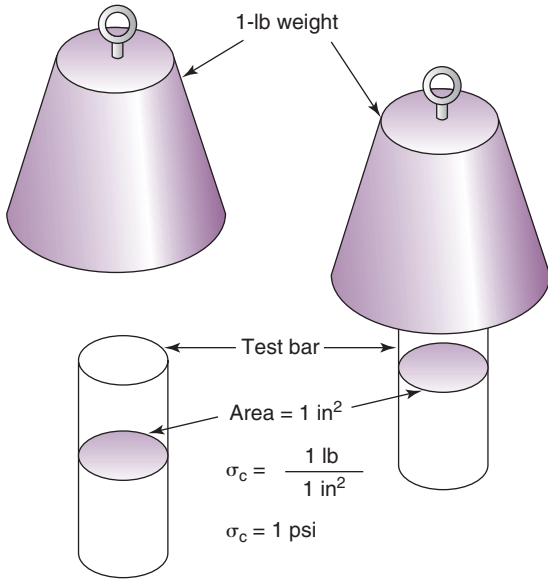


Figure 2.2 Compressive stress on a cylinder. *psi*, Pounds per square inch.

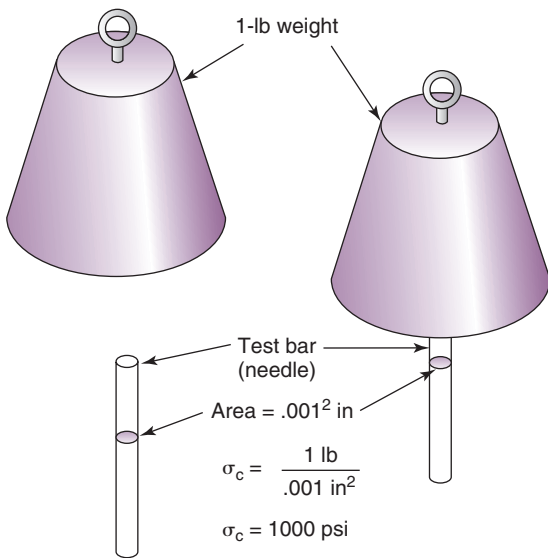


Figure 2.3 Compressive stress on a needle. *psi*, Pounds per square inch.

Tensile Stresses

Tensile stresses directly pull apart an object or cause it to be in *tension*. Tensile stresses occur parallel to the line of force but perpendicular to the area in question (Fig. 2.5). If an object is pulled at both ends, it is in tension, and sufficient force will pull it apart. Two children fighting over a fish scale and exerting opposing forces put it in tension, as shown by the indicator on the scale (Fig. 2.6). Strings are a good example of objects that typically can only have tension applied.

Compressive Stresses

Compressive stresses act to squeeze or compress objects. They also occur parallel to the line of force and perpendicular to the cross-sectional area (Fig. 2.7).

A blacksmith shapes metal by hitting the material with a hammer to squeeze or compress the metal into the desired shape. In the same

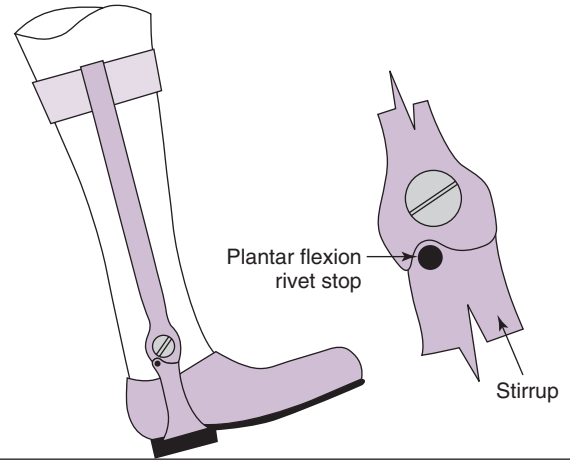


Figure 2.4 Ankle-foot orthosis with 90-degree plantar flexion stop.

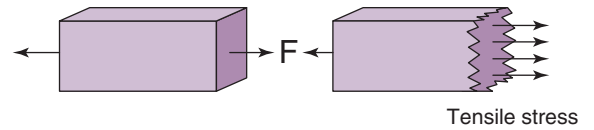


Figure 2.5 Tension. *F*, Force.

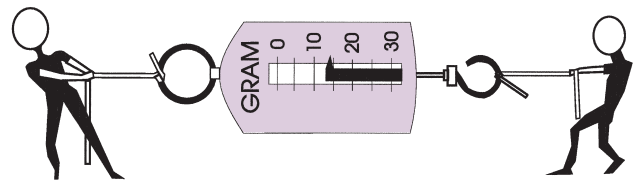


Figure 2.6 Spring scale used to demonstrate tension.

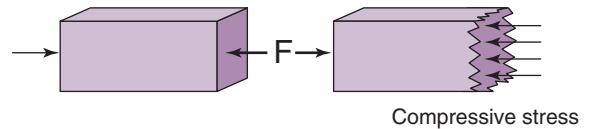


Figure 2.7 Compression. *F*, Force.

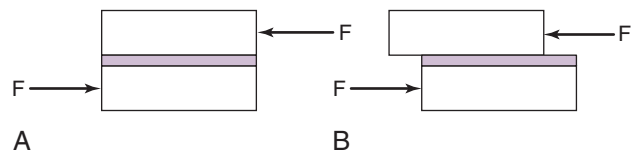


Figure 2.8 Shear. *F*, Force.

manner, clay yields to low compressive stress. Clay is distorted and squeezed out of shape by comparatively small forces. Many materials may be strong in compression and relatively weak in tension. The opposite can also be true.

Shear Stresses

Shear stresses act to scissor or shear the object, causing the planes of the material to slide over each other. Shear stresses occur parallel to the applied forces. Consider two blocks (Fig. 2.8A) with their surfaces bonded together. If forces acting in opposite directions are applied to these blocks, they tend to slide over each other. If these forces are great enough, the bond between the blocks will break (Fig. 2.8B). If the area

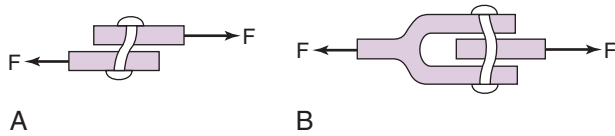


Figure 2.9 Joint shear. F , Force.

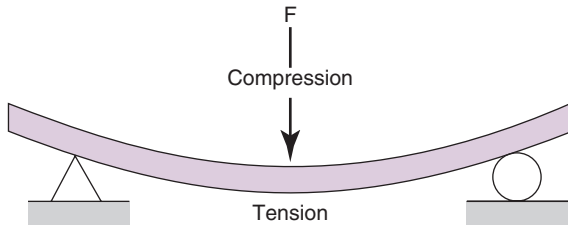


Figure 2.10 Flexure. F , Force.

of the bonded surfaces were increased, however, the effect of the forces would be distributed over a greater area. The average stress would be decreased, and there would be increased resistance to shear stress.

A common lap joint and clevis joint are examples of a shear pin used as the axis of the joint (Fig. 2.9). The lap joint has one shear area of the rivet resisting the forces applied to the lap joint (see Fig. 2.9A), and the rivet in the box joint (clevis) has an area resisting the applied forces that is twice as great as the area in the lap joint (assuming that the rivets in both joints are the same size; see Fig. 2.9B). Consequently the clevis joint will withstand twice as much shear force as the lap joint. The lap joint also has less resistance to fatigue (fluctuating stress of relatively low magnitude, which results in failure), because it is more susceptible to flexing stresses.

Flexural Stress

Flexural stress (bending) is a combination of tension and compression stresses. Beams are subject to flexural stresses. When a beam is loaded transversely, it will sag. The top fibers of a beam are in maximum compression while the bottom side is in maximum tension (Fig. 2.10). The term *fiber*, as used here, means the geometric lines that compose the prismatic beam. The exact nature of these compressive and tensile stresses is discussed later.

Yield Stress

The yield stress or yield point is the point at which the material begins to maintain a deformational change because of the load and therefore the internal stresses under which it has been exposed. Before this point the material is behaving in its elastic zone—that is, any deformation moves back to its original position.

Ultimate Stress

Ultimate stress is the stress at which a material ruptures. The strength of the material before it ruptures also depends on the type of stress to which it is subjected. For example, ultimate shear stresses usually are lower than ultimate tensile stresses (i.e., less shear stress must be applied before the material ruptures than in the case of tensile or compressive stress).

Strain

Materials subjected to any stress will deform or change their shape, even at very small levels of stress. If a material lengthens or shortens in response to stress, it is said to experience *strain*. Strain is denoted

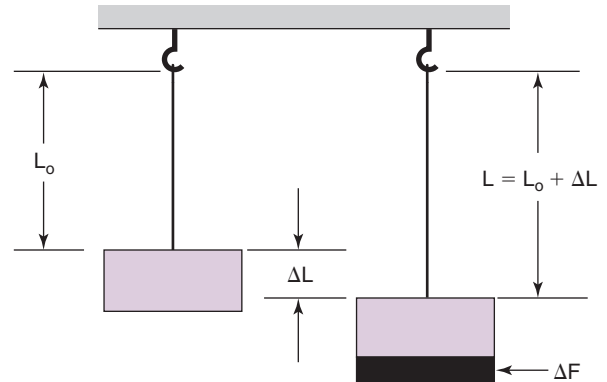


Figure 2.11 Strain. F , Force; L , length.

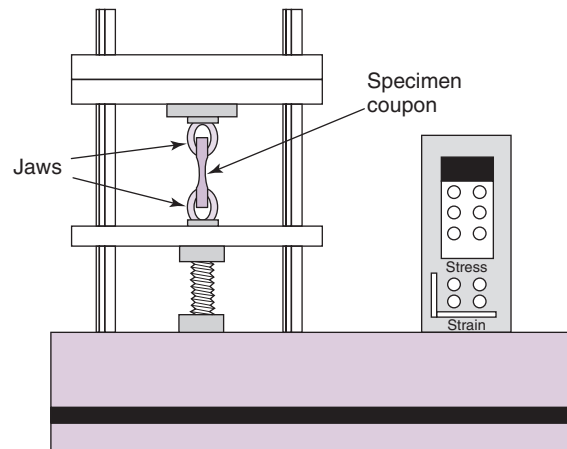


Figure 2.12 Tension test.

by ϵ and can be found by dividing the total elongation (or contraction) ΔL by the original length L_0 of the structure being loaded:

$$\epsilon = \frac{\Delta L}{-L_0} \quad (2.2)$$

Consider a change in length ΔL of a wire or rod caused by a change in stretching force F (Fig. 2.11). The amount of stretch is proportional to the original length of wire.

Stress–Strain Curve

The most widely used means of determining the mechanical properties of materials is the tension test. Much can be learned from observing the data collected from such a test. In the tension test, the shape (dimensions) of the test specimen are fixed by standardization so that the results can be universally understood, no matter where or by whom the test is conducted. The test specimen is mounted between the jaws of a tensile testing machine, which is simply a device for stretching the specimen at a controlled rate. As defined by standards, the cross-sectional area of the test specimen is smaller in the center to prevent failures where the test specimen is gripped. The specimen's resistance to being stretched and the linear deformations are measured by sensitive instrumentation (Fig. 2.12).

The force of resistance divided by the cross-sectional area of the specimen is the *stress* in the specimen (Eq. 2.1). The *strain* is the total deformation divided by the original length (Eq. 2.2). If the stresses in the specimen are plotted as ordinates of a graph, with the accompanying strains as abscissae, a number of mechanical properties are graphically

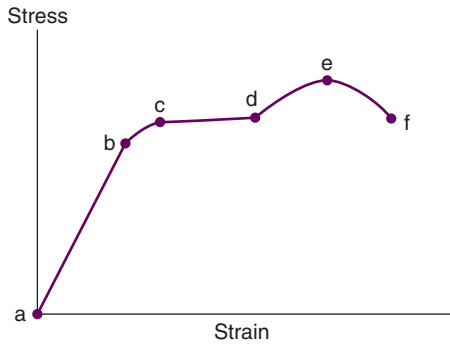


Figure 2.13 Stress–strain.

revealed. Fig. 2.13 shows such a typical stress–strain diagram for a mild steel specimen.

The shape and magnitude of the stress–strain curve of a metal depend on its composition; heat treatment; history of plastic deformation; and strain rate, temperature, and state of stress imposed during testing. The parameters used to describe the stress–strain curve of a metal are tensile strength, yield strength or yield point, percent elongation, and reduction in area. The first two are strength parameters; the last two indicate ductility, or the material’s ability to be stretched (and remain stretched) under tension.

The general shape of the stress–strain curve (see Fig. 2.13) requires further explanation. In the region from *a* to *b*, the stress is linearly proportional to strain, and the strain is elastic (i.e., the stressed part returns to its original shape when the load is removed). When the applied stress exceeds the yield strength, *b*, the specimen undergoes plastic deformation. If the load is subsequently reduced to zero, the part remains permanently deformed. The stress required to produce continued plastic deformation increases with increasing plastic strain (points *c*, *d*, and *e* on Fig. 2.13)—that is, the metal strain hardens. The volume of the part remains constant during plastic deformation, and as the part elongates, its cross-sectional area decreases uniformly along its length until point *e* is reached. The ordinate of point *e* is the tensile strength of the material. After point *e*, further elongation requires less applied stress until the part ruptures at point *f* (breaking or fracture strength). Although this seems counterintuitive, it actually occurs and is best sensed when bolts are overtorqued. Correct torque settings should always be complied with, but practitioners commonly torque bolts using the “as hard as possible” technique, assuming that this method somehow secures the bolt more appropriately than the correct torque and a thread-locking solution. When excessive torque has been applied, the bolt first feels like it has loosened before failing. This simply reflects the fact that the yield point of the material has been surpassed and the bolt is plastically deforming under a decreasing load to failure.

Stress–strain diagrams assume widely differing forms for various materials. Fig. 2.14A shows the stress–strain diagram for a medium-carbon structural steel. The ordinates of points *p*, *u*, and *b* are the yield point, tensile strength, and breaking strength, respectively. The lower curve of Fig. 2.14B is for an alloy steel, and the higher curve is for hard steels. Nonferrous alloys and cast iron have the form shown in Fig. 2.14C. The plot shown in Fig. 2.14D is typical for rubber. Note that these are representative graphs only. The dimensions (and scale) vary greatly for the materials mentioned here.

For any material with a stress–strain curve of the form shown in Figs. 2.14, it is evident that the relationship between stress and strain is linear for comparatively small values of the strain. This linear relationship between elongation and the axial force causing it was first reported

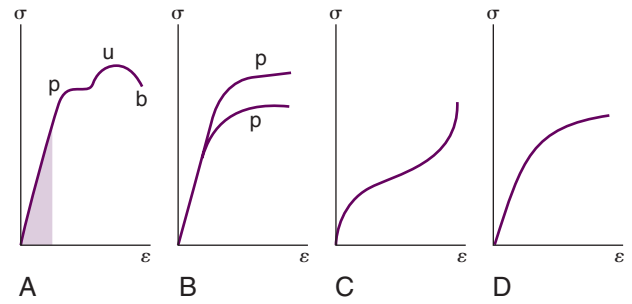


Figure 2.14 Stress (σ) - Strain (ϵ) diagrams for different materials.

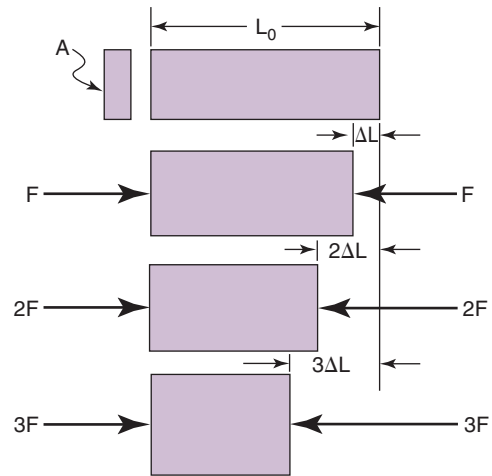


Figure 2.15 Linearity. *F*, Force; *L*, length.

by Sir Robert Hooke in 1678 and is called *Hooke’s law*. Expressed as an equation, Hooke’s law becomes:

$$\sigma = E\epsilon \tag{2.3}$$

where σ = stress (psi), ϵ = strain (inch/inch), and E = constant of proportionality between stress and strain. This constant is also called *Young’s modulus* or the *modulus of elasticity*.

The slope of the stress–strain curve from the origin to point *p* (see Figs. 2.14A and 2.14B) is the modulus of elasticity of that particular material E . The region where the slope is a straight line is called the *elastic region*, where the material behaves in what we typically associate as an elastic manner; that is, it is loaded and stretched, and upon releasing the load the material returns to its original position. The ordinate of a point coincident with *p* is known as the *elastic limit* (i.e., the maximum stress that may develop during a simple tension test such that no permanent or residual deformation occurs when the load is entirely removed). Values for E are given in Table 2.1. Devices and materials are designed to perform in the elastic region (with very few exceptions).

In a routine tension test (Fig. 2.15), which illustrates Hooke’s law, a bar of area A is placed between two jaws of a vise, and a force F is applied to compress the bar. Combining Eqs. 2.1, 2.2, and 2.3 and solving for the shortening ΔL gives:

$$\Delta L = \frac{FL_0}{AE} \tag{2.4}$$

Because the original length L_0 , cross-sectional area A , and modulus of elasticity E are constants, the shortening ΔL depends solely on F . As F doubles, so does ΔL .