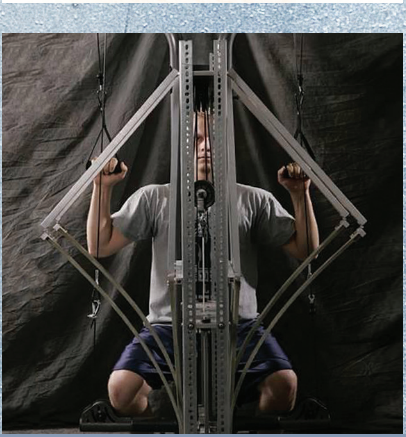
Editors LARRY L. HOWELL SPENCER P. MAGLEBY BRIAN M. OLSEN

HANDBOOK OF COMPLIANT MECHANISMS



WILEY

Handbook of Compliant Mechanisms

Handbook of Compliant Mechanisms

Edited by

Larry L. Howell
Brigham Young University, USA
Spencer P. Magleby
Brigham Young University, USA
Brian M. Olsen
Los Alamos National Laboratories, USA

WILEY
A John Wiley & Sons, Ltd., Publication

This edition first published 2013
© 2013 John Wiley & Sons Ltd.

Registered Office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ,
United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data

Handbook of compliant mechanisms / edited by Professor Larry Howell, Dr. Spencer P. Magleby, Dr. Brian M. Olsen.
pages cm
Includes bibliographical references and index.
ISBN 978-1-119-95345-6 (cloth)
1. Mechanical movements. 2. Machinery, Kinematics of. 3. Engineering design. I. Howell, Larry L., editor. II. Magleby, Spencer P., editor. III. Olsen, Brian M. (Brian Mark), 1983– editor.
TJ181.H25 2013
621.8–dc23
2012037077

Set in 10/12pt Palatino by Aptara Inc., New Delhi, India

Contents

PART ONE INTRODUCTION TO COMPLIANT MECHANISMS

PART TWO MODELING OF COMPLIANT MECHANISMS

PART THREE SYNTHESIS OF COMPLIANT MECHANISMS

PART FOUR LIBRARY OF COMPLIANT MECHANISMS

List of Contributors

Chapter Contributors

Shorya Awtar – Assistant Professor, University of Michigan, Ann Arbor, MI, USA
Mary Frecker – Professor, The Pennsylvania State University, University Park, PA, USA
Jonathan Hopkins – Assistant Professor, University of California, Los Angeles, CA, USA
Larry Howell – Professor, Brigham Young University, Provo, UT, USA
Brian Jensen – Associate Professor, Brigham Young University, Provo, UT, USA
Charles Kim – Assistant Professor, Bucknell University, Lewisburg, PA, USA
Girish Krishnan – Post-Doctoral Associate, University of Michigan, Ann Arbor, MI, USA
Craig Lusk – Associate Professor, University of South Florida, Tampa, FL, USA
Spencer Magleby – Associate Dean, Brigham Young University, Provo, UT, USA
Chris Mattson – Associate Professor, Brigham Young University, Provo, UT, USA
Brian Olsen – Research Engineer, Los Alamos National Lab, Los Alamos, NM, USA

Managing Library Contributors

G. K. Ananthasuresh – Indian Institute of Science, Bangalore, Bangalore, India
Guimin Chen – Xidian University, Xi’an, P.R. China
Martin Culpepper – Massachusetts Institute of Technology, Cambridge, MA, USA
Mohammad Dado – University of Jordan, Amman, Jordan
Haijun Su – Ohio State University, Columbus, OH, USA
Simon Henein – CSEM Centre Suisse d’Electronique et de Microtechnique SA, Neuchâtel, Switzerland
Just L. Herder – Delft University of Technology, Delft, The Netherlands
Jonathan B. Hopkins – University of California, Los Angeles, CA USA
Nilesh D. Mankame – General Motors Research & Development, Warren, MI, USA
Ashok Midha – Missouri University of Science and Technology, Rolla, MO, USA

Anupam Saxena – Indian Institute of Technology, Kanpur, Kanpur, India
Umit Sonmez – American University of Sharjah, Sharjah, UAE
Jingjun Yu – Beihang University, Beijing, China

Library Contributors

Imad F. Bazzi – General Motors Research & Development, Warren, MI, USA
Shusheng Bi – Beihang University, Beijing, China
Ozgur Erdener – Istanbul Technical University, Istanbul, Turkey
Bilin Aksun Güvenç – Okan University, Istanbul, Turkey
Huseyin Kızıl – Istanbul Technical University, Istanbul, Turkey
Xu Pei – Beihang University, Beijing, China
Ahmet Ekrem Sarı – Altinay Robot Technologies, Istanbul, Turkey
Nima Tolou – Delft University of Technology, Delft, The Netherlands
Levent Trabzon – Istanbul Technical University, Istanbul, Turkey
Cem Celal Tutum – Technical University of Denmark, Lyngby, Denmark
Hongzhe Zhao – Beihang University, Beijing, China
Guanghua Zong – Beihang University, Beijing, China
Yörükoğlu, Ahmet – R&D Engineer at Arcelik

Student Contributors

Bapat, Sushrut – Missouri University of Science and Technology
Barg, Matt – Brigham Young University
Berg, Fred van den – Delft University of Technology
Black, Justin – Brigham Young University
Bowen, Landen – Brigham Young University
Bradshaw, Rachel – Brigham Young University
Campbell, Robert – Brigham Young University
Chinta, Vivekananda – Missouri University of Science and Technology
Dario, P. – Scuola Superiore Sant'Anna
Davis, Mark – Brigham Young University
Demirel, Burak – KTH Royal Institute of Technology
Duffield, Luke – Brigham Young University
Dunning, A.G. – Delft University of Technology
Emirler, Mümin Tolga – Istanbul Technical University
Foth, Morgan – Brigham Young University
George, Ryan – Brigham Young University
Güldoğan, Bekir Berk – Istanbul Technical University
Greenberg, Holly – Brigham Young University
Hardy, Garrett – Brigham Young University
Harris, Jeff – Brigham Young University
Howard, Marcel J. – Delft University of Technology

Ivey, Brad – Brigham Young University
Jones, Andrea – Brigham Young University
Jones, Kris – Brigham Young University
Kluit, Lodewijk – Delft University of Technology
Koecher, Michael – Brigham Young University
Koli, Ashish – Missouri University of Science and Technology
Kosa, Ergin – Istanbul Technical University
Kragten, Gert A. – Delft University of Technology
Kuber, Raghvendra – Missouri University of Science and Technology
Lassooij, Jos – Delft University of Technology
McCort, Ashby – Brigham Young University
Morsch, Femke – Delft University of Technology
Morrise, Jacob – Brigham Young University
Pate, Jenny – Brigham Young University
Peterson, Danielle Margaret – Brigham Young University
Ratlamwala, Tahir Abdul Husain – University of Ontario Institute of Technology
Reece, David – Brigham Young University
Samuels, Marina – Brigham Young University
Sanders, Michael – Brigham Young University
Shafiq, Mohammed Taha – American University of Sharjah
Shelley, Dan – Brigham Young University
Shurtz, Tim – Brigham Young University
Simi, Massimiliano – Scuola Superiore Sant'Anna
Skousen, Darrell – Brigham Young University
Solomon, Brad – Brigham Young University
Steutel, Peter – Delft University of Technology
Stubbs, Kevin – Brigham Young University
Tanner, Daniel – Brigham Young University
Tekeş, Ayşe – Istanbul Technical University
Telford, Cody – Brigham Young University
Toone, Nathan – Brigham Young University
Wasley, Nick – Brigham Young University
Wengel, Curt – Brigham Young University
Wilding, Sam – Brigham Young University
Williams, David – Brigham Young University
Wright, Doug – Brigham Young University
Yu, Zhiwei – Beihang University
Zhao, Shanshan – Beihang University
Zirbel, Shannon – Brigham Young University

Acknowledgments

The *Handbook of Compliant Mechanisms* is a result of work by contributors from around the world. Compliant mechanisms experts have authored the chapters in Parts II and III, and many more have contributed entries to the *Library of Compliant Mechanisms* (Part IV of the *Handbook*). The contributions of these individuals are gratefully acknowledged.

We express appreciation to Brian Winder and Jonathan Hopkins for their work on early drafts of the *Library of Compliant Mechanisms*. The graphic design assistance of Jung-Ah Ahn (Jade) and Stephen Jensen are acknowledged, as is the administrative assistance of Danielle Peterson. The format of the *Library of Compliant Mechanisms* was inspired by Ivan I. Artobolevskii's seven-volume work *Mechanisms in Modern Engineering Design: A Handbook for Engineers, Designers, and Inventors*. We also wish to honor the memory of Dr. Umit Sonmez, who passed away unexpectedly during the time that he was contributing to the *Handbook.*

Preface

Compliant mechanisms are seeing expanded use because they offer advantages such as increased performance (e.g. high precision, low weight, low friction), lower cost (e.g. simplified manufacture, low part count), and ability to miniaturize (e.g. makes possible micro- and nanomechanical devices). However, because compliant mechanisms are relatively new compared to more traditional devices, it is difficult for designers to find examples and resources to guide them in their work. Many people are beginning to understand the advantages of compliant mechanisms but there is still a general lack of knowledge of how to implement them. Although many journal articles and some texts are available to aid in the in-depth engineering of compliant mechanisms, a more concise and visual resource is needed to provide inspiration and guidance in the conceptual stages of compliant mechanism design.

The *Handbook of Compliant Mechanisms* is intended to provide a summary of compliant mechanism modeling and design methods and a broad compilation of compliant mechanisms that will provide inspiration and guidance to those interested in exploiting the advantages of compliant mechanisms in their designs. Early *Handbook* chapters provide basic background in compliant mechanisms, summaries of some of the major methods for designing compliant mechanisms, categories of compliant mechanisms, and an example of how the *Handbook* can be used to facilitate compliant mechanism design. Graphics and brief descriptions of many compliant mechanisms are provided to give inspiration in preliminary design.

The *Handbook of Compliant Mechanisms* is designed to be a resource for engineers, designers, and others involved in product design. We hope that it is found to be useful by many in the development of compliant mechanisms.

The *Handbook* is divided into the following Parts:

Part I provides an introduction to compliant mechanisms and describes how to use the *Handbook* to design compliant mechanisms.
Part II focuses on modeling of compliant mechanisms.
Part III describes methods for the synthesis of compliant mechanisms.
Part IV is a visual library of compliant mechanisms.

We wish to express our sincere thanks to all the contributors that worked to make this handbook possible. We hope that it is found to be useful in creating new compliant mechanism designs.

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-0800606. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Brian M Olsen is an employee of Los Alamos National Security, LLC, the operator of Los Alamos National Laboratory for the US Department of Energy. The views expressed in this book are solely those of Brian and the other authors and do not necessarily reflect the views, positions and opinions of the US Department of Energy or the US Government.

Larry L. Howell
Brigham Young University, USA

Spencer P. Magleby
Brigham Young University, USA

Brian M. Olsen
Los Alamos National Laboratory, USA

November 2012

Part One

Introduction to Compliant Mechanisms

1

Introduction to Compliant Mechanisms

Larry L. Howell

Brigham Young University, USA

1.1 What are Compliant Mechanisms?

If something bends to do what it is meant to do, then it is compliant. If the flexibility that allows it to bend also helps it to accomplish something useful, then it is a compliant mechanism [1]. The idea of using compliant mechanisms in products is catching on, but traditionally when designers need a machine that moves, they commonly use very stiff or rigid parts that are connected with hinges (like a door on its hinge or a wheel on an axle) or sliding joints. But when we look at nature we see an entirely different idea from rigid parts connected at joints – most moving things in nature are very flexible instead of stiff, and the motion comes from bending the flexible parts [2]. For example, consider your heart – it is an amazing compliant mechanism that started working before you were born and will work all day every day for your entire life. Think of bee wings, elephant trunks, eels, sea weed, spines, and the blooming of flowers (Figure 1.1) – all of which are compliant. Even the natural motions that seem to be exceptions to this bending behavior, like your knee or elbow, use cartilage, tendons, and muscles to do their work. We see in nature the possibility of making machines that are very compact – a mosquito (Figure 1.1) is able to fly while carrying its own on-board navigation, control, energy harvesting, and reproduction systems. Would it be possible for us to improve human-designed products if we applied the lessons learned from nature and looked to flexibility to achieve movement?

It is interesting that some early man-made machines were compliant mechanisms. Is that because we were closer to nature then? An example of a compliant mechanism with a multi-millennia history is the bow (Figure 1.2). Ancient bows were made using a composite of bone, wood, and tendon, and they used the flexibility of their limbs to

---

Handbook of Compliant Mechanisms, First Edition. Edited by Larry L. Howell, Spencer P. Magleby and Brian M. Olsen.

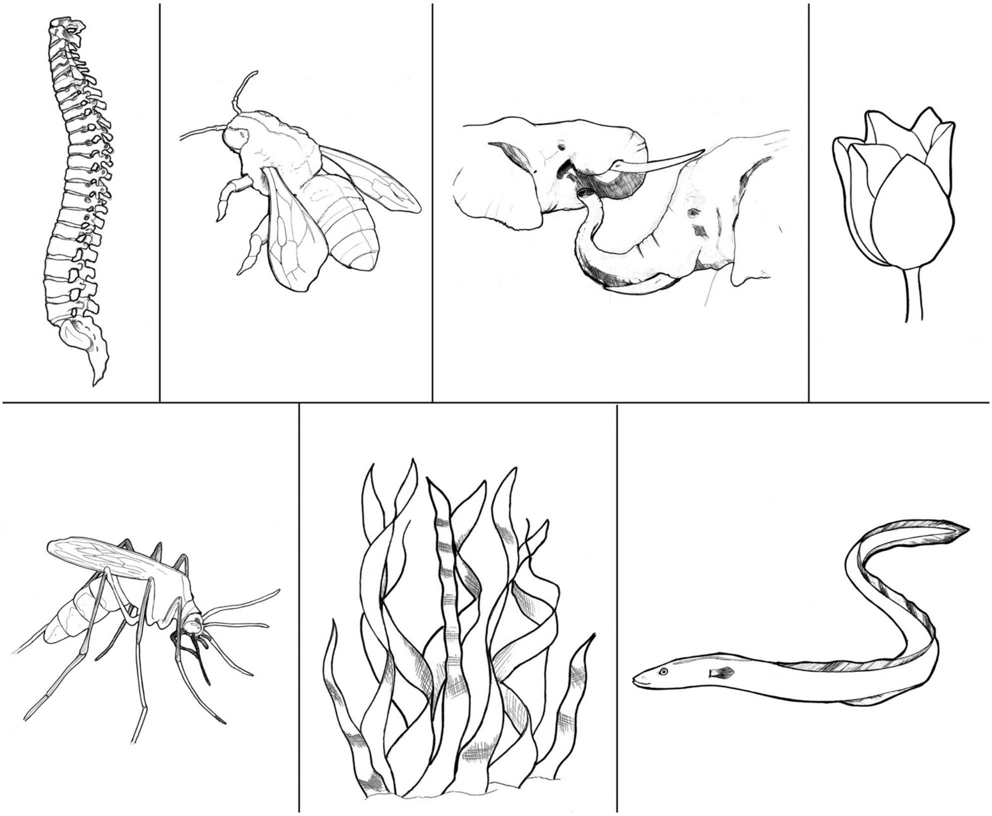


Figure 1.1 A few examples of compliance in nature: a spine, bee wings, elephant trunks, blooming flowers, a mosquito, sea weed, and eels

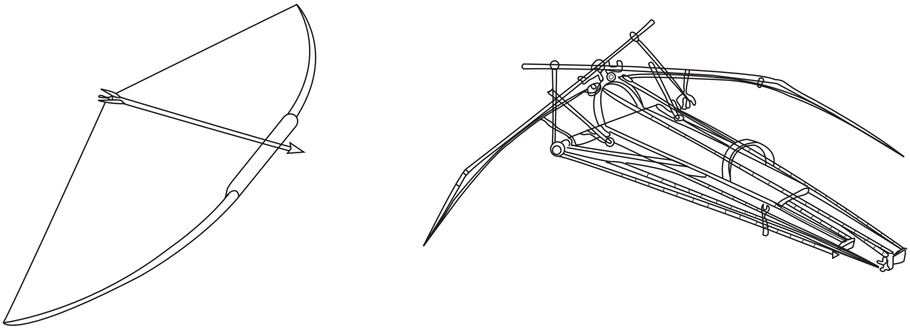


Figure 1.2 Early compliant mechanism designs include the ancient bow and many compliant mechanism designs by Leonardo da Vinci

Figure 1.3 The Wright brothers used wing warping to achieve control of their aircraft for sustained human flight

store energy that would be released into propelling the arrow. It is interesting to see the sketches of Leonardo da Vinci [3] and see many compliant mechanisms (see Figure 1.2 for an example). Even one of the great achievements of engineering – sustained human flight – began with a compliant mechanism when the Wright brothers (Figure 1.3) used wing warping to achieve control of their early aircraft [4].

This may all sound good, but it turns out that compliant mechanisms can be difficult to design. Nature has done it, but nature employed very different design methods from those we mortals use. Great strides were made in the design of machines when compliance was left to nature and we moved to the much easier-to-design realm of rigid parts connected at hinges. For example, the too-sophisticated-for-its-time wing warping of the Wright Flier was eventually replaced by the much-easier-to-work-with control surfaces provided by an aileron pivoting on a hinge.

However, over the past few decades our knowledge has advanced. We have developed new materials, increased our computational capabilities and expanded the ability to design more sophisticated devices. At the same time, society has developed new needs that cannot be easily addressed using traditional mechanisms. This means that there is an increased ability to create compliant mechanisms, and an increased motivation for doing so. As an example, reconsider the example of aircraft control. The Wright Flier started out with wing warping for its control surfaces, but other aircraft quickly moved to approaches using traditional mechanisms. But with the increased computational power available and improved materials that have been developed, researchers are returning to the idea of wing warping to get the advantages, such as reduced weight, that would come from the approach.

One of the things that make traditional design of mechanical components compelling is that designers can separate different functions to be done by different parts, and each part is assigned to do that one function. The blessing and curse of compliant mechanisms is that they integrate different functions into fewer parts. Compliant mechanisms may be able to accomplish complex tasks with very few parts, but they can be much more difficult to design.

1.2 What are the Advantages of Compliant Mechanisms?

The integration of functions into fewer parts leads to compelling advantages for compliant mechanisms. For one, there is a potential for significantly lower costs. This comes from reduced assembly, fewer components to stock, and the possibility of simplified manufacturing (such as fabricating a mechanism from a single mold).

Another advantage is the potential for increased performance. This includes high precision [5, 6] due to reduced wear and reduced or eliminated backlash. The low weight of compliant mechanisms can be useful for shipping and for weight-sensitive applications such as spacecraft. Eliminating the need for lubrication at joints is also a useful performance improvement that is helpful in many applications and environments.

Another category of advantages lies in the ability to miniaturize compliant mechanisms. Microelectromechanical systems (MEMS) for example, are often fabricated from planar layers and compliant mechanisms offer a way to achieve motion with the extreme constraints caused by the resulting geometry (Figure 1.4) [7, 8]. Compliant mechanisms will likely be central to the creation of nanoscale machines.

1.3 What Challenges do Compliant Mechanisms Introduce?

While the advantages of compliant mechanisms are amazing, they also have some challenges that have to be carefully considered in their design. For example, the

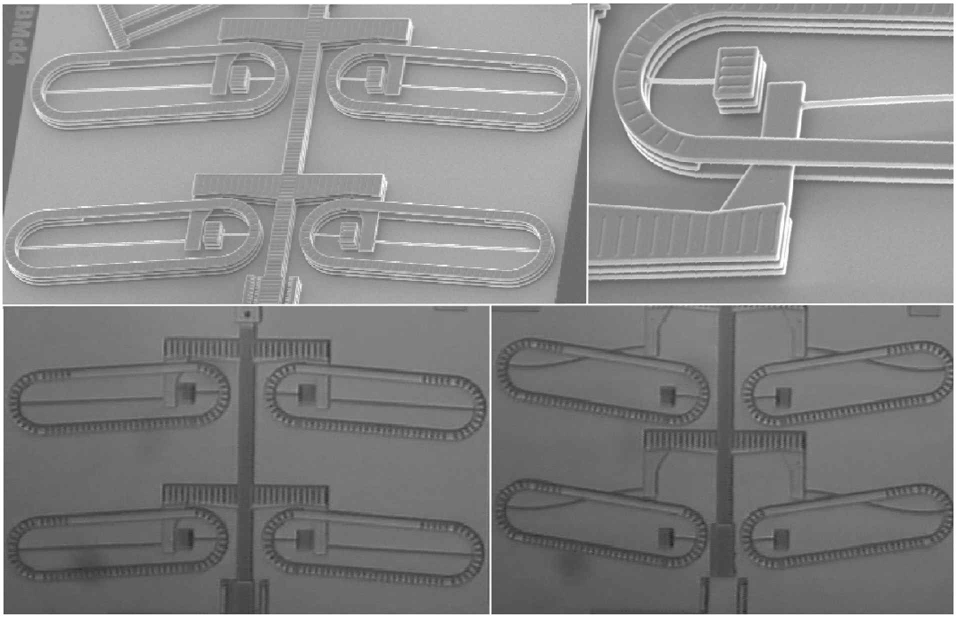


Figure 1.4 A multi-layer compliant microelectomechanical system (MEMS). A scanning electron micrograph of the device (top left) with a close up of compliant segments (top right), and the device shown in two stable equilibrium positions (bottom)

integration of different functions into fewer parts offers advantages, but it also requires the simultaneous design for motion and force behavior. This difficulty is increased further by the fact that the deflections are often well into the nonlinear range and simplified linear equations are not adequate to define their motion.

Fatigue life needs to be addressed for most compliant mechanisms. Because their motion comes from bending of flexible parts, compliant mechanisms experience stress at those locations. When that motion is repeated during its life, fatigue loads are present and the fatigue life must exceed the expected life of the mechanism. Fortunately, methods for analyzing and testing fatigue life are available to help design compliant mechanisms for their needed fatigue life (see Chapter 2), but it requires special attention and effort to ensure that the mechanism has the life required.

Although properly designed and tested compliant mechanisms can achieve needed fatigue life, there can still be a consumer perception that flexible components are flimsy or weak. This can be a particular concern where the flexible component is visible to the consumer and it may require special care in the design for adequate life and for its appearance.

The motion of compliant mechanisms is often more limited than for traditional rigid-link mechanisms. For example, a shaft connected to bearings has the ability to undergo continuous revolution, whereas the motion of a flexible component will be limited by the deflection it can undergo before failure.

The fact that strain energy is stored in a deflected beam can be either an advantage or a disadvantage. Advantages include that a compliant element integrates both a spring and hinge function into a single component providing a "home" position where the device will go when unloaded. This integration also allows certain behaviors, such as bistability (the characteristic of having two distinct preferred positions, such as the on-off positions of a light switch) [9]. However, there are times when these qualities are not desired, and the properties become a disadvantage in the device design.

If certain materials are held under stress for long periods of time or at elevated temperatures, they can take on a new shape associated with the stressed position. This is called "stress relaxation." Some compliant mechanisms have functions where they must maintain positions where they are under stress, and so are subject to stress relaxation conditions. This requires careful design and thoughtful choice of material.

1.4 Why are Compliant Mechanisms Becoming More Common?

Advances in our understanding of compliant mechanisms, combined with general technological developments, have resulted in a rapid growth in compliant mechanism applications (the library portion of this handbook is a testament to that growth). These applications range from high-end, high-precision devices to ultralow-cost packaging; from nanoscale featured components to large-scale machines; from weapons to healthcare products.

We mentioned that many early devices were compliant mechanisms, but then rigid-link devices connected at hinges gained favor because of the simplicity offered for analysis and design. So what is different now and why are there so many more compliant mechanisms than before? The answer lies at least partly in technological advances that have been made over recent decades. For example, new materials are available that are well suited for compliant mechanisms. There have been dramatic improvements in computational hardware and software available to analyze compliant mechanism motion and stresses. Developers and researchers have also increased our ability to design and analyze compliant mechanisms. Considerable effort has gone into creating methods to facilitate compliant mechanism design (some of the resulting methods are summarized in this handbook). There is also an increased awareness of the advantages of compliant mechanisms. As some commercial applications have been successful, they provide examples and inspiration for other applications to follow. Finally, as society and technology have advanced, new needs have risen, and some of these needs are best addressed by compliant mechanisms. This includes devices at very small size scales, devices with relatively complex motion but must be made at extremely low cost, compact medical implants, and high-precision machines.

1.5 What are the Fundamental Concepts that Help Us Understand Compliance?

There are a few straightforward but counterintuitive concepts that can help us understand the fundamentals of compliant mechanisms.

1.5.1 Stiffness and Strength are NOT the Same Thing

Usually when we want something to be strong (meaning that we don't want it to break), we also want it to be stiff (meaning that we don't want it to bend). For example, the floor in the upper story of a building we want to be both stiff and strong. We obviously don't want it to break, but we also don't want it to move around when people walk on it. So it needs to be stiff and strong. The crank shaft in an engine? Stiff and strong. A bridge? Stiff and strong. A desk? Stiff and strong.

We so often design things that need to be both stiff and strong that it is easy for our intuition to begin to tell us that stiffness and strength are the same. But they are NOT the same. Strength relates to resistance to failure, while stiffness relates to resistance to deflection. These are different and are governed by different properties. Consider a piece of steel with a rectangular cross section as shown in Figure 1.5. The steel will withstand a certain stress until it will fail. But its strength is the same whether it is loaded about its thin or thick axis (assuming it is isotropic), while its stiffness is very different for these two conditions.

1.5.2 It is Possible for Something to be Flexible AND Strong

Consider examples of things that are both flexible and strong. Flexible endoscopes, such as that shown in Figure 1.6, are used to examine the interior parts of the body. The endoscope must be flexible to undergo the required motion and to minimize any trauma from its use within the body. It must also be strong to withstand the loads that it will undergo during its use. As another example, consider the pulleys on the cables of a ski lift (Figure 1.7). They must be strong enough to reliably lift the skiers to their destination but must be flexible enough to go around the pulleys.

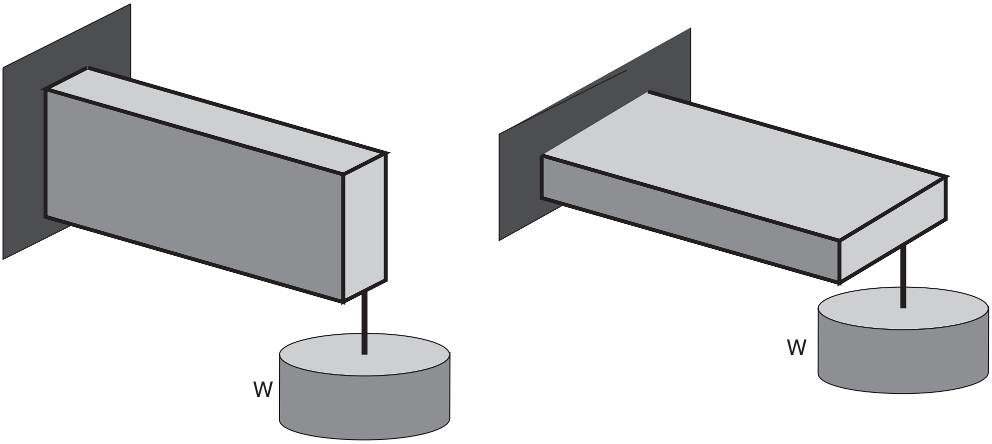


Figure 1.5 The rectangular piece of steel may have the same strength in different directions, but it will have very different stiffness for the two orientations shown

So why is it that many things we want to be stiff and strong, but others we want to be flexible and strong? What is it that determines the difference between these two situations? The answer lies in whether the device needs to hold a force, or if it needs to be deflected (like a cable going around a pulley). A bridge is an example of something that needs to be stiff and strong because we want it to hold the weight of

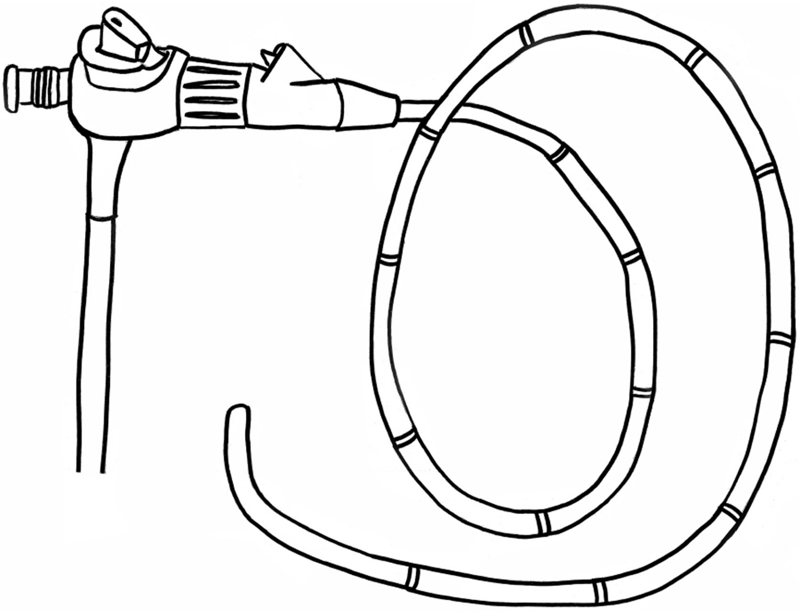


Figure 1.6 A flexible endoscope is an example of a device that needs to be both flexible and strong

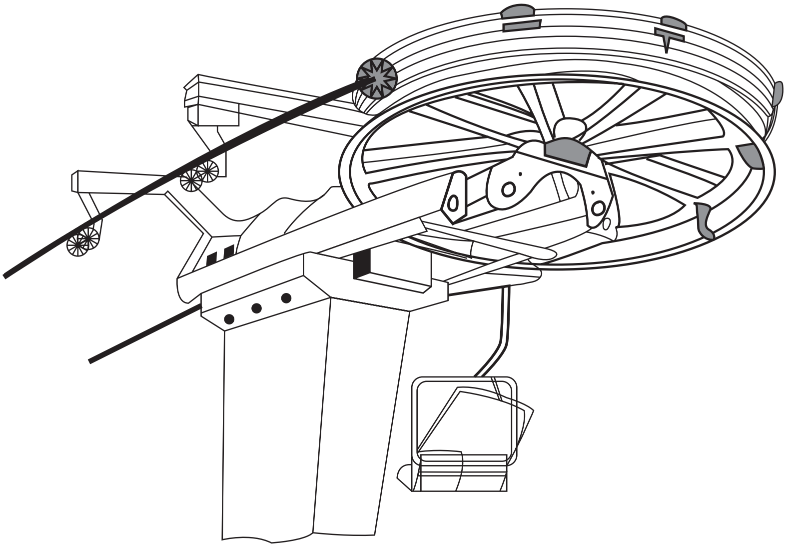


Figure 1.7 A ski lift cable must be flexible enough to go around the pulley and strong enough to carry the loads

traffic going across them without moving. The endoscope and the pulley cable are both examples of things that need to bend to perform their function. If they were too stiff, they would be overstressed and would break when they were forced to undergo the needed motion. So if something needs to hold a weight or other force, it should be stiff and strong; if it needs to go through a certain deflection, it should be flexible and strong.

1.5.3 The Basics of Creating Flexibility

There are three primary ways that we can influence flexibility. These are

1. material properties (what it is made of);
2. geometry (its shape and size);
3. loading and boundary conditions (how is it held and loaded).

Each of these is described below.

1.5.3.1 Materials Properties

Different materials have different stiffnesses as measured by the material's Young's modulus (or modulus of elasticity). Consider the three rods in Figure 1.8. Each rod has identical size and shape and each has the same size weight hanging from it, but they are each made of a different material: steel, aluminum, and polypropylene. The Young's modulus of steel (207 GPa) is about three times that of aluminum (72 GPa), so for the same geometry and same weight, the aluminum rod will deflect three times