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题目《神经科学原理》（第三十三章）英汉翻译实践报告

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研究方向（领域）英语笔译（工程科技翻译）

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A Report on E-C Translation of Chapter Thirty-three of *Principles of Neural Science*

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A Report on the E-C Translation Practice of Chapter Thirty-three of *Principles of Neural Science*

You Ziqing

A thesis submitted in conformity with the requirements

For the degree of Master of

Translation and Interpreting

In English Translation

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School of Foreign Studies

Anhui Polytechnic University

Wuhu

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摘 要

本报告的原材料节选自《神经科学原理》(第五版)，该著作被称为“神经科学圣经”，由埃里克 R. 坎德尔（Eric R. Kandel）主编。笔者选取第三十三章作为翻译文本，本章主要探究运动与神经科学的关系，涉及大量的专业术语以及长难句，专业性逻辑性较强，结构严谨。

在翻译过程中，专业术语的翻译和长难句的翻译是笔者遇到的突出难点。就专业术语翻译的问题，笔者使用多种工具查阅专业术语，查阅平行文本，咨询神经科学领域专家以及参与实验等途径以求最佳翻译；就长难句翻译的问题，笔者采取显化其隐含意，转换语态，分译法等策略，以适应目标语言的写作习惯，确保翻译逻辑清晰，提高译文的可读性，从而提升读者的阅读体验。

通过此次翻译实践和案例分析，笔者的翻译能力在精确翻译专业术语和确保句子流畅度方面均得到了显著提升。笔者学会了运用不同的翻译策略解决各类翻译问题。此外，笔者也深刻认识到科技英语翻译是国际间科技信息交流的重要手段之一，做好该领域的翻译工作对于我国引进先进技术，推进国家之间的科技交流起着至关重要的作用。

经笔者多平台、多渠道检索，目前尚未发现源文本的中文译本。由于该书背景资料详实，专业性和科学性完全符合科技文本的基本

特征，且准确翻译极具挑战性，因此十分适合作为翻译源文本。最后，笔者期望本次翻译实践能够在一定程度上为从事科技文本翻译的工作者提供方法论上的参考。

关键词：《神经科学原理》；科技英语翻译；神经科学；信息型文本；显化隐含意

Abstract

The source text of this report is extracted from the fifth edition of *Principles of Neuroscience*, which is known as the “bible of neuroscience” and edited by Eric R. Kandel. The translator chose Chapter 33 as the translation text, which mainly explores the relationship between exercise and neuroscience. In the logical and professional text with well-organized structure, there are a large number of terminologies and long sentences

During the translation practice, the translation of terminologies and long sentences are the major difficulties. In terms of terminology translation, the translator used a variety of tools to look up the terminology, search for parallel texts, consult experts in the field of neuroscience and participate in experiments in order to get the best translation. In terms of long sentences translation, the translator adopted the strategies of manifesting the implicit meaning, converting voice and dividing sentences to conform to Chinese expression habits, so as to make the logic clear, enhance the readability of the translated text and improve the reading experience of readers.

Through this translation practice and case study, the translator’s translation ability has been further improved from the accuracy of translating terminology to the fluency of translating sentences. Also, she has learnt to solve various translation problems through different

translation strategies. In addition, the translator also deeply realizes that scientific and technological English translation is one of the important means of international exchange of scientific and technological information, and doing a good job of translation in this field plays a vital role in introducing advanced technology to our country and promoting scientific and technological exchanges between countries.

It is worth mentioning that the Chinese translation of the original text has not yet been found even through various platforms and channels were searched. The book with its professional and scientific features has detailed background information, which is fully in line with the basic characteristics of scientific and technological texts. To achieve a satisfying Chinese equivalence of the text is quite challenging. So this text is very suitable to be used as a source text for translation. The translator hopes that this translation practice might provide methodological reference for other people engaged in the translation of scientific and technological texts to a certain extent.

Key Words: *Principles of Neural Science*; scientific and technical English translation; neuroscience; informative texts; manifesting implicit meaning

Contents

Chapter 1 Task Description

1.1 Task Background

The Chinese translation of the original text has not yet been found in multiple platforms and channels. The translation task is Chapter 33 of the book *Principles of Neuroscience*, with a total of 8606 words in the source language and 19721 words in the target language (including footnotes), which is in line with the requirement of the word count of the dissertation for master's degree in translation.

In the realm of neuroscience, the intricate complexities of the human brain have long been a subject of fascination and inquiry. Advances in technology and methodologies have enabled researchers to delve deeper into understanding the brain's functions, structures, and the underlying mechanisms of neurological disorders. However, the dissemination of this knowledge across different linguistic barriers poses a significant challenge.

In recent years, neuroscience research has become a popular field, and its application value in medicine, psychology, artificial intelligence and other fields has been gradually recognized. With the increase of international exchanges, academic books and papers in the field of neuroscience have been emerging. The Neuroscience Translation Practice Report aims to introduce the international advanced neuroscience research progress and achievements into China, and promote the development of neuroscience field in China, so as to provide scholars, doctors, and researchers in the related fields in China with useful references and lessons.

1.2 Source of the Task

The text selected for translation from the book *Principles of Neuroscience* focuses on the brain and behavior, examining these from both microscopic and macroscopic perspectives. Specifically, Chapter 33 delves into the realm of motor functions, discussing commandments, signals, and systems related to movement. The source text exhibits a logical and impartial approach, abundant in specialized terminology and lengthy sentences that are intricately linked through conjunctions and adverbs. Within this text, the usage of non-finite verbs, prepositional phrases, and the passive voice is notably recurrent.

1.3 Significance of the Practice

Neuroscience is an interdisciplinary field covering biology, psychology, physics and philosophy. With the acceleration of globalization and the popularization of scientific knowledge, academic exchanges and cooperation in the field of neuroscience have become more and more important. In this context, the translation practice in the field of neuroscience is of great significance.

First of all, translation practice in the field of neuroscience helps to promote international academic exchanges. Due to language and cultural differences, there are often barriers of communication between scholars from different countries and regions. With translation and interpretation, the latest research results, academic ideas and technological advances can be spread from one language to another, helping scholars from different countries and regions to better understand each other. So, translation can not only accelerate the progress of academic research, but also help promote international cooperation and common development.

Secondly, the translation practice in the field of neuroscience helps to improve the quality and level of translation. As neuroscience involves a wide range of fields and is highly specialized, it requires translators to have a high level of academic literacy and professional knowledge. Through the translation practice, the experience and lessons gained from the translation process have been summarized to improve the translator's translation level and ability.

In conclusion, the translation practice in the field of neuroscience is of great significance. It can not only promote international academic communication and cooperation, improve the quality and level of translation, but also promote the development and progress of neuroscience field. Therefore, we should pay attention to the translation practice in the field of neuroscience, strengthen academic exchanges and cooperation, and jointly promote the development and progress of the field of neuroscience artificial intelligence. China possesses substantial prowess in the realm of high-tech development, which has led to the enhancement of people’s living standards. Consequently, engaging in translation activities is instrumental in advancing research into the integration of brain and computer systems, with the goal of establishing more sophisticated artificial neural networks—a crucial element within the domain of artificial intelligence.

Chapter 2 Pre-translation Preparations

Translation activity is a complex process, and pre-translation preparation is the first step. Doing a good job of pre-translation preparation and carefully analyzing the original text can help translators understand the whole text in depth, grasp the overall idea of translation, and reduce the burden of specific translation practice in the later stage. The preparations might include analyzing the type of the text, using proper translation tools, building a glossary of terminology, and choosing parallel texts in the related field.

2.1 Analysis of the Source Text

Newmark suggests that informative texts encompass materials such as textbooks, technical reports, newspaper or journal articles, scientific publications, theses, and meeting minutes or agendas. The essential aspect of the informative function of language is the conveyance of "truth"—reflecting the external circumstances, the factual aspects of the subject matter, and the tangible reality beyond the linguistic expression (Newmark, 2001a: 40).

For the purpose of translation study, a passage from *Principles of Neural Science* was selected. This text primarily explores the subjects of the brain and behavior on both microscopic and macroscopic levels. Specifically, Chapter 33 delves into the subject of motor functions, discussing elements such as commands for movement, signals related to motion, and the systems that facilitate it. The source text is characterized by its logical and unbiased nature, featuring a wealth of specialized terminology and complex sentences that are intricately linked through conjunctions and adverbs. The usage of non-finite verbs, prepositional phrases, and the passive voice is prevalent throughout. Overall, the text exhibits traits consistent with the characteristics of an informative text.

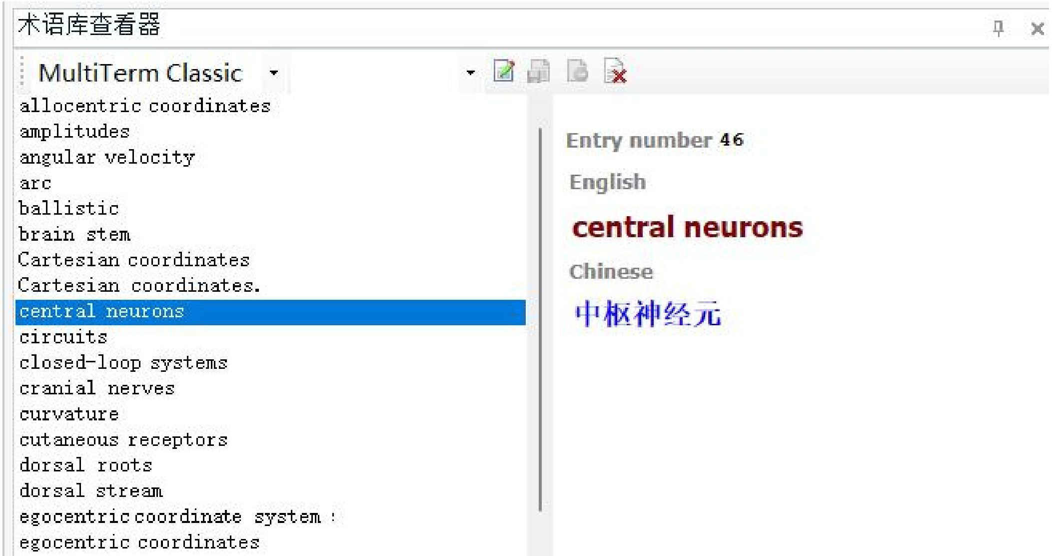
Newmark suggests that communicative translation strategies should be applied to scientific and technical English, irrespective of whether the text is informative or evocative. The primary step in this translation approach is to understand the central message of the source text and to discern its style, ensuring that the translated work mirrors this style to the greatest extent possible. Moreover, it is crucial to recognize the structural composition of the original text and the interrelationships between its sections to create a coherent and smooth translation that is readily comprehensible to the target audience. Communicative translation prioritizes the target language, focusing not only on the accurate transmission of the contextual meaning from the source text but also on enhancing the accessibility and acceptability of its content and form to the target readers. This approach contrasts with free translation, as it maintains a strong fidelity to the communicative intent of the original text. Communicative translation aims to produce an effect, leading to translations that are more fluent, natural, and attuned to the linguistic habits of the target language.

2.2 Translation Tools

First, the translator searched the Internet and downloaded the PDF version of the book *Principles of Neuroscience* and used some tools for translation (see Table 1). Before importing the text into Trados, she double-checked whether the text in Trados was consistent with the text in the book. If any inconsistencies were found, she corrected them in Trados and then typeset the text, separating the information in the main text from the information in the graphs and charts. She then read the full text. The first reading was aimed at getting the general idea. The second reading was aimed at marking and searching for words she did not know and then with the help of the Oxford Advanced Learner's English-Chinese Dictionary to determine their meanings. In case of technical terms, the translator firstly searched for these terms mainly on Wikipedia to understand their background knowledge information, and then looked up their meanings and verified their meanings on Term online and Xiangya Medical Dictionary Online. Afterwards, she used Multiterm to add and annotate the term (see Figure 1). Then, the translator exchanged terms with her classmates who translated the same book to find out if there were any errors. Finally, the translator exported the terms from Multiterm and created a glossary, as shown in Appendix I.

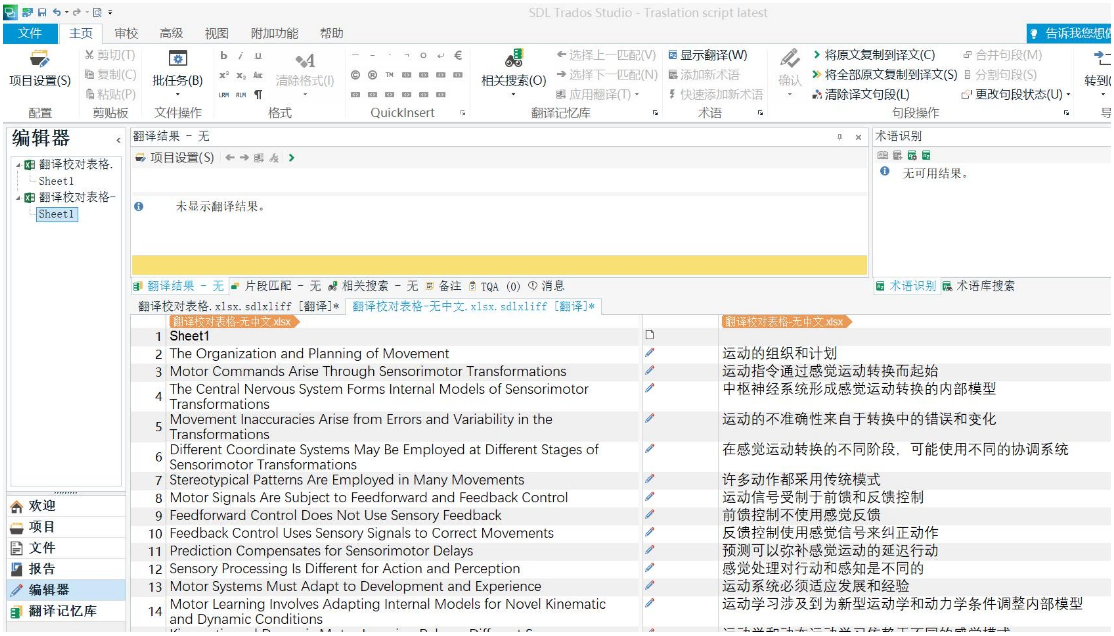
Table 1 Translation Tools Used in the Project

Category	Name	Purpose
Books	Comparison and Translation Between English and Chinese	To check out and master translation techniques and strategies to deal with difficulties in translating
	Scientific Translation	To have a firm grasp of translation techniques and strategies to deal with difficulties in translating scientific texts
A Dictionary	Oxford Advanced Learner's English-Chinese Dictionary	To determine meanings of unknown words
Online Resources	Termonline	To verify terms that were determined
	Wikipedia	To provide background information
	CNKI	To search articles to deal with difficulties in Translating and determine terms in the text
	Xiangya Medical Dictionary Online	To determine the meaning of medical terms
Translation Software	Trados Studio 2021	To edit and export translation, create translation memory, and ensure the consistency of translation
	Multiterm 2022	To make, manage, and export a glossary, and show terms in Trados while translating
		Xiangya Medical Dictionary Online
Quality Control Software	Xbench	To revise normal errors of translation such as the consistency of terms



(Figure 1 The Glossary of the Text)

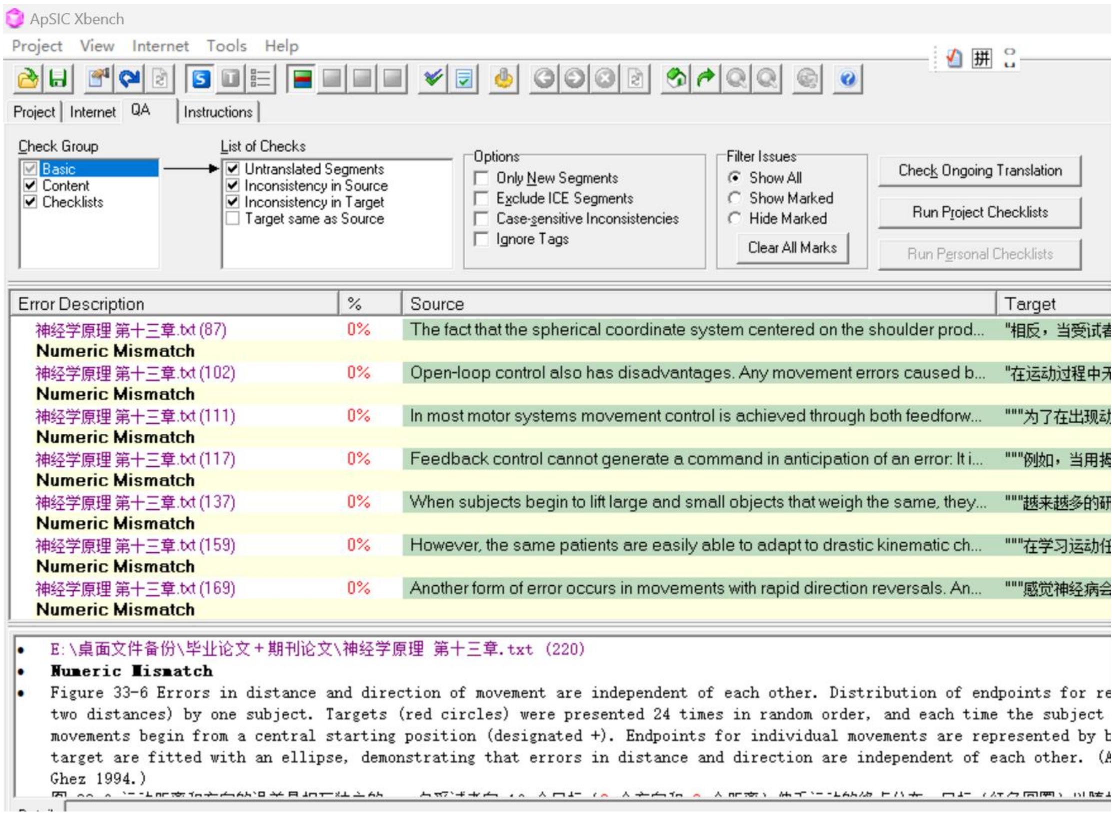
In this process, the translator edited the translation in Trados (see Figure 2). When something confusing was found in the text, for the related keywords were searched on CNKI to get the relevant text and the background knowledge. When encounters difficulties in translation were encountered, such as the conversion of passive voice, the translator searched for relevant articles on CNKI, compared the translations of similar texts, learned the translation skills and strategies of that similar text, and then read the book *English-Chinese Comparison and Translation* and *English for Science and Technology* to master the translation skills and strategies. As for the terminology, since a glossary has been established, its meaning is directly displayed in Trados, as shown in Figure 1.



(Figure 2 Translating in Trados)

After making the first version of the translation in Trados, the translator exported the translation and put it into the form of bilingual cross-referenced table in excel, and then exchanged revisions and discussed them with the students who translated the same book to mark the words and sentences which are difficult to be understood (see Figure 3). Then, the translator used Xbench, a quality control software, to check whether there were any normal errors, such as untranslated segments, inconsistencies between the source text and the target text, numerical mismatches, mismatches of key terms, repeated words and segments (see Figure 4). Afterwards, she revised her translation based on the results shown by Xbench.

(Figure3 revised by companions)



(Figure 4 Quality Control in Xbench)

The translator then checked the accuracy, fluency, coherence and logic of her translation. She modified the incorrect or obscure parts of it. After that, the translator revised the translation based on some suggestions from her tutor and classmates. Finally, the translator read her translation in its entirety to make sure that it is smooth and coherent and readable. If it is not fluent, she revised it again.

2.3 Parallel Text

In 1980, the British scholar Hartmann delineated three types of parallel texts: Type A signifies translations that maintain high degrees of formal consistency and semantic equivalence with the original text; Type B denotes translations that exhibit partial formal consistency and functional equivalence; and Type C pertains to corpora that align with registers, lacking semantic equivalence but sharing some consistency in subject matter, style, context, and textual object (赵军峰, 周婷, 2016). For this translation practice, the translator selected Type C as a guide, referring to texts related to neuroscience that matched in terms of usage scenario, object, and style.

To guarantee accuracy and professionalism in the translation, the translator faced difficulties finding explanations for certain terms in dictionaries and translating the long sentences of neuroscience. Therefore, she extensively studied parallel texts related to neuroscience, such as *Neurobiology-From Neuron to Brain*, *Cognitive Neuroscience: The Biology of the Mind*, *Cognition* and *Mathematical Foundation of Neuroscience*, which helped translator to gain a comprehensive understanding of the neuroscience and maintain the style and linguistic characteristics of text. Valuable theoretical and practical knowledge was obtained, which greatly supported the translation work.

In essence, parallel texts are akin to a companion piece that mirrors the content of the original. They serve an essential function in scientific and technological translation. Parallel texts serve to bridge any gaps in the translator’s expertise within the realm of science and technology, facilitating a deeper understanding of the source material. This, in turn, aids in achieving efficient, precise, and genuine translations, thereby enhancing the overall quality of the translation work. When engaging with parallel texts, translators have the opportunity to become acquainted with authentic language usage, which can elevate their ability to discern the quality of translations. Furthermore, by contemplating the unique attributes and merits of the original texts, as well as the issues present in the target texts, translators can strive to make the translated works more credible and expertly crafted.

2.4 Glossary Building

The original text contains a large number of professional terms, such as central neurons, etc. Therefore, the translator listed the terms and phrases in the text before translation, and then made use of dictionaries and parallel texts to get their translations. At the same time, the translator discussed with the team members to unify the terminology expressions and to ensure the consistency and completeness of the translation and to avoid mistranslation. As a result, a list of terms and proper nouns was established, which is shown in the Appendix I.

Chapter 3 Case Analysis

This part gives a case analysis of some typical translation problems the translator encountered in her practice, such as the difficulties in achieving complete equivalence of professional terms and normal words in combination with the context and professional background, in handling punctuation and passive voice, and in maintaining text logic and coherence. The translator tried to solve the problems of vocabulary by adopting translation strategies and instrumental methods. For the translation of double dashes and passive voice, such strategies as omission and conversion are adopted. For the translation of adverbial clauses and long sentences, which affects the text’s logic and coherence, the translator adopted the methods of adjusting the order of sentences and division. For the translation of gerund clauses and long sentences that affect the logic and coherence of the text, the translator adopted the methods of adjusting the word order and division.

3.1 Achieving Accuracy of Terminology

The key point of scientific and technical translation is to convey the actual content of the original material, which is by no means the arithmetic sum of the meanings of individual words. Instead, the source text is a specific and complete information structure built up by a number of words (professional and non-professional, real and functional) in accordance with certain rules and in a certain way(朱纯深, 1987:20-23).

In the face of unfamiliar or new terminology, it is easy to search for resources such as dictionaries to no avail. In this case, we often search the web page first to get a general understanding of the background, and then check other resources, which is also in line with general search habits. However, information from news reports is often redundant and repetitive and accuracy cannot be guaranteed, and forum encyclopedias are often crowdfunded in an open and autonomous manner, where translations are mostly provided by web users, so further validation is required. CNKI and other mega-databases consisting of huge amounts of full-text data and basic information materials can greatly improve the efficiency and quality of searching per unit of time for the background of terminology definitions and even translations（卢植，胡健 2019：72-77）.

3.1.1 Consulting the Parallel Text of Neuroscience

The naming of scientific and technological terms is mostly in favor of the principle of action, structural characteristics or components, resulting in the proliferation of compound and phraseological scientific and technological terms. In this practice, there are some terminologies whose meanings are difficult to be determined. In this case, consulting the parallel text of neuroscience is quite useful.

Example 1：

Source Text (ST): Pacinian corpuscles in the skin are activated and a burst of action potentials occurs in the afferent **RA2 fibers**, signaling the beginning of the hold phase during which the grip force is constant. The absence of **RA2 signals** triggers a slow increase in force that is terminated when lifting begins.

Target Text 1(TT1): 当受试者开始举起一个 400 克的物体时，皮肤中的帕氏体被激活，传入 **RA2 纤维**出现动作电位爆发，标志着握力恒定的保持阶段开始。**RA2 信号**的缺失引发了力量的缓慢增加，当开始举起时，力量的增加被终止。

TT2: 当受试者开始举起一个 400 克的物体时，皮肤中的帕氏体被激活，传入**快适应感受器二类（RA2）纤维**出现动作电位爆发，标志着握力恒定的保持阶段开始。**快适应感受器二类（RA2）信号**的缺失引发了力量的缓慢增加，当开始举起时，力量停止增加。

Analysis:

In example 1, the challenge of translation is primarily associated with the neurobiological terms “*RA2 fibers*” and “*RA2 signals*”, whose Chinese equivalent terms could not be got directly through search engine and online terminology data base. In TT1, the translator resorted to using the abbreviated forms of these terms, which could potentially hinder comprehension among readers.

As mentioned above, CNKI and other mega-databases consisting of huge amounts of full-text data and basic information materials can greatly improve the efficiency and quality of searching per unit of time for the background of terminology definitions and even translations. The translator utilized CNKI to look up the terms "*RA2 fibers*" and "*RA2 signals*," discovering they are respectively abbreviated versions of "rapidly-adapting receptor 2 fibers" and "rapidly-adapting receptors 2 signals," with their Chinese translations being "*快适应感受器二类纤维*" and "*快适应感受器二类信号*, "as confirmed by Term-online. To ensure precision and maintain professional standards in translation, the translator cross-referenced with the text "*Neurobiology-From Neuron to Brain*," verifying the accuracy of these Chinese renderings. Therefore, in TT2, the full form of abbreviations is translated and the short forms are shown with parentheses, namely, "*适应感受器二类（RA2）纤维*" and "*快适应感受器二类（RA2）信号*", thus enhancing the clarity of the translation for readers.

Example 2:

ST: This copy of the motor command is known as an **efference copy (or corollary discharge)** to signify that it is a copy of the **efferent signal** flowing from the central nervous system to the muscles. We will see later how such simulations can be learned and used in sensorimotor control.

TT1: 这个运动指令的拷贝被称为**效应拷贝（或推理放电）**，表示它是一个从中枢神经系统流向肌肉的**效应信号**的拷贝。我们将在后面看到这种模拟是如何被学习和用于感觉运动控制的。

TT2: 这个运动指令的拷贝被称为**感知副本（或伴随放电）**，表示它是一个从中枢神经系统流向肌肉的**感知信号**的拷贝。我们将在后面看到这种模拟是如何被学习和用于感觉运动控制的。

Analysis:

In example 2, the primary challenge in translation is attributed to the neurobiological terms "*efference copy*" and "*corollary discharge*", which do not have direct Chinese equivalents that can be easily identified through search engines or online terminology databases. In TT1, the translator translated these terms literally, neglecting the context. Subsequently, a search was conducted on Baidu, where the terms yield multiple explanations: "*效应拷贝*" and "*推理放电*"， as well as "*感知副本*"and "*伴随放电*". As previously discussed, databases such as CNKI, containing vast quantities of full-text resources and foundational information, can significantly enhance the efficiency and quality of terminology searches. As for the two terms, "*推理放电*" is a theory while "*伴随放电*" is a medical term for the study of the human brain according to CNKI. To guarantee accuracy and professionalism in the translation, the translator studied the parallel text *Mathematical Foundation of Neuroscience*, confirming that the translations "*感知副本*" , "*伴随放电*" and "*感知信号*" are correct. Therefore, in TT2, in order to fit in the text type and enhance the readability, the term "*corollary discharge*" is translated into "*伴随放电*", while the term "*efference copy*" is translated into "*感知副本*"and "*efferent signal*" is translated into "*感知信号*"accordingly.

Example 3：

ST: A. Spatial orientation. To reach for an object, the object and hand are first located visually in a coordinate system relative to the head (**egocentric coordinates**).

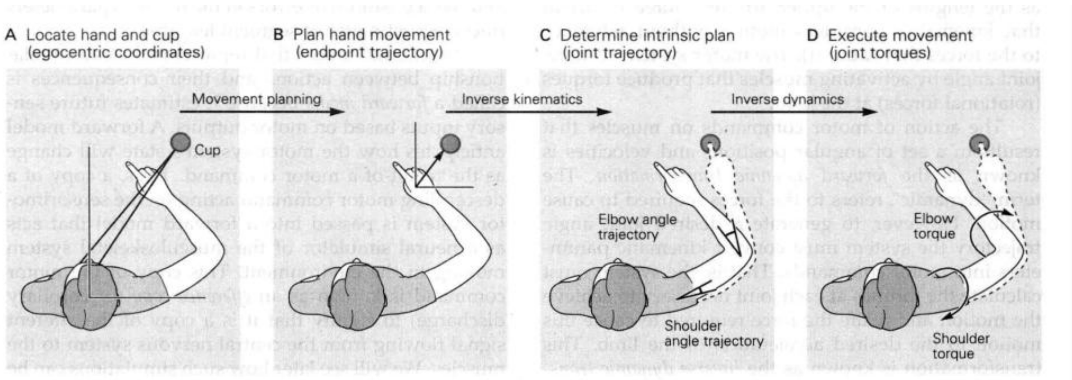
TT1: A.空间定向。要伸手去拿一个物体，首先要在相对于头部的坐标系**（中心坐标）**中对物体和手进行视觉定位。

TT2: A.空间定向。要伸手去拿一个物体，首先要在相对于头部的坐标系**（自我中心坐标）**中对物体和手进行视觉定位。

Analysis:

In example 3, the challenge of translation primarily emerges from the neurobiological terms "*egocentric coordinates*", which cannot be directly retrieved through a search engine or an online terminology database for their Chinese equivalents. In TT1, the translator translated the term "*egocentric coordinates*" into "*中心坐标*" literally, a translation that lacks further validation.

The term "*egocentric coordinates*" was searched in Baidu, in which its possible translation "*自我中心坐标*" and relevant background information was found. As previously noted, databases like CNKI, containing vast quantities of full-text data and foundational information, can significantly enhance the efficiency and quality of terminology background research in a given timeframe. Consequently, the translator searched the term through CNKI, finding that the term“*自我中心坐标*” is indeed a technical term in neuroscience. According to the context and as shown in the chart below, the experiment is to determine the direction of the object and hand based on the subject himself. “*中心坐标*” is not so accurate to express the real meaning of the source text. To ensure fidelity and expertise in translation, the translator studied the parallel text *Cognitive Neuroscience: The Biology of Mind and Cognition*, confirming that the translation “*自我中心坐标*” is correct. Therefore, In TT2, the translator rendered “*egocentric coordinates*” into “*自我中心坐标*”, a choice that not only corroborates the findings from CNKI but also aligns with the chart below and the parallel text, thus enhancing readability and clarifying the translation.



3.1.2 Participating in Experiments and Consulting Experts of Neuroscience

Consulting experts in the field of neuroscience and participating in experiments of neuroscience are of great help to translate terms that are difficult to define even in online terminology databases or parallel texts.

Example 4:

ST：<u>Movement inaccuracies</u> arise from errors and variability in the transformations

TT1：<u>运动的不准确性</u>来自于转换中的误差和变化

TT2：<u>运动误差</u>来自于转换中的误差和变化

Analysis:

In example 4， the difficulty of translation mainly lies in the neurobiological terms “*movement inaccuracies*”, whose Chinese equivalent terms could not be got directly through search engine and online terminology data base. In TT1, the translator translated the term "*movement inaccuracies*" into "*运动的不准确性*" which was not validated further.

Subsequent to conducting a search for "*movement inaccuracies*" on Baidu, the potential translation"*运动的不准确性*" along with pertinent background information was retrieved. However, as previously stated, the reliability of information obtained from web pages cannot be guaranteed since translations are typically contributed by internet users, necessitating additional validation. Consequently, the translator sought guidance from experts in the field of neuroscience, who confirmed that "*运动误差*" is a technical term used in neuroscience experiments. The translator then participated the experiment of neuroscience in person, finding that the term "*运动误差*" is commonly employed in the experiment of neuroscience, especially in the process of analyzing the experiment data. Therefore, the term "*movement inaccuracies*" should be translated into"*运动误差*" to clarify the eccentric meaning of the source text. TT2 validated its translation through participating in experiments and consulting experts in the field of neuroscience, thereby enhancing the clarity and precision of the translation.

Example 5:

ST: For example, the **vestibulo-ocular reflex** uses open-loop control to maintain fixation during head rotation.

TT1: 例如，**前庭-眼反射**使用开环控制来保持头部旋转时的定点。

TT2: 例如，**前庭-眼动反射**使用开环控制来保持头部旋转时的定点。

Analysis:

In example 5, the translation challenge is centered around the neurobiological term "*vestibulo-ocular reflex*", whose Chinese equivalent terms could not be got directly through search engine and online terminology data base. In TT1, the term "*vestibulo-ocular reflex*" was translated into "*前庭-眼反射*" literally, a rendition that lacks further validation.

Then, the term "*vestibulo-ocular reflex*" was searched in Baidu, in which its possible translation “*前庭-眼反射*” and relevant background information could be found. To guarantee accuracy and professionalism in the translation, the translator sought assistance from experts in the field of neuroscience. These experts confirmed that “*vestibulo-ocular reflex*” is a technical term utilized in neuroscience experiments. The translator then personally engaged in a neuroscience experiment to collect data on eye movement, observing that “*前庭-眼动反射*” is commonly used in the context of such experiments. Therefore, in TT2, the term “*vestibulo-ocular reflex*” is translated into“*前庭-眼动反射*”to clarify the eccentric meaning of the source text. TT2 validated its translation through participating in experiments and consulting experts in the neuroscientific field, thereby enhancing the readability and accuracy.

Example 6:

ST：We know from cellular studies that the central nervous system contains internal representations (“**neural maps**”) of the various sensory receptor arrays and the musculature

TT1：我们从细胞研究中得知，中枢神经系统包含各种感觉受体阵列和肌肉组织的内部表征（“**神经元地图**”）。

TT2：我们从细胞研究中得知，中枢神经系统包含各种感觉受体阵列和肌肉组织的内部表征（“**神经元映射**”）。

Analysis:

In example 6, the primary difficulty in translation is associated with the neurobiological term “*neural maps*,” which does not have direct Chinese equivalents that can be readily found through search engines or online terminology databases. A search for "neural maps" on Baidu yielded the potential translation “*神经元地图*”along with relevant background information. In TT1, the term "neural maps" was translated literally into “*神经元地图*.”

To guarantee accuracy and professionalism in the translation, the translator sought advice from experts in the field of neuroscience. It was confirmed that the term“*神经元映射*” is a technical term used in neuroscience experiments. Then the translator participated the experiment of neuroscience in person, finding that the term "*神经元映射*"is often used in the experiment of neuroscience, especially in the process of analyzing the experiment data. Therefore, in TT2, the term "*neural maps*" was translated into"*神经元映射*" to clarify the eccentric meaning of the source text. TT2 validated its translation through participating in experiments and consulting experts in the field of neuroscience, enhancing the translation's readability and accuracy.

3.2 Shifting Sentence Structures

The syntax in English is different from that in Chinese. Many elements vary considerably in usage, such as punctuations, passive voice and adverbial modifier. In this section, several cases are presented to show the syntactic fluency with appropriate methods.

3.2.1 The Manifestation of Implicit Meanings in the Passage of Neuroscience

Chinese sentences are organized by meanings, different from the hypotactic English sentences which need punctuation marks to show logic（曾曾，2012:35）. Dashes are seldom used and are hard to function as parenthesis in Chinese. Furthermore, in Chinese scientific and technological text, transition and emphasis are the functions of dashes（滕安利，1992：48）.

When the double dashes in the original text only play the logical connecting role of supplementary explanation, and the interjections between the double dashes are only semantically connected with their modifying parts, or when the double dashes in the original text are only used to connect two parallel structures, retaining the form of double dashes in the translation will result in the semantic interruption of the Chinese sentences. Therefore, when translators translate this kind of sentences containing double dashes, they should adopt the method of omission, adjust the word order and add logical connectives appropriately according to the context of the translated text and Chinese writing habits, so as to retain the logical connecting function of the double dashes in the original sentences. In that way, the translation will be more in line with the Chinese language's expression habits.

Parentheses serve as a valuable tool to enhance the readability of text; however, their misuse can detract from this effect. When the content enclosed within parentheses is closely related to the main sentence, it can lead to a decrease in readability. Moreover, if the relationship between the annotation and the annotated element is not delineated by parentheses, the text may become ambiguous (兰宾汉, 2006).

In the context of translating parentheses within chemical texts, the cohesion theory provides a framework for considering three translation strategies: (1) maintaining the parentheses if their function remains the same in both source and target languages and if the information within is of minor importance in the text, (2) omitting the parentheses when such a removal aids reader comprehension, provided that the content within is crucial, and (3) replacing parentheses with other punctuation marks if the source text's parentheses serve the same purpose as those marks do in the target language (丁希萍, 2020). Here are some examples about the manifestation of implicit meaning of double dashes and parenthesis in sentences of neuroscience.

Example 7:

ST: Although movements are often classified according to function<u>—</u>eye movements, prehension (reach and grasp), posture, locomotion, breathing, and speech<u>—</u>many of these functions are subserved by overlapping groups of muscles.

TT1: 虽然运动通常按照功能进行分类<u>——</u>眼球运动、前视（伸手和抓握）、姿势、运动、呼吸和说话<u>——</u>但是这些功能中有不少共同参与的肌肉群。

TT2: 按照功能，运动通常可以分<u>**为：**</u>眼球运动、前视（伸手和抓握）、姿势、运动、呼吸和说话。然而，这些功能中有不少共同参与的肌肉群。

Analysis:

In example 7, the difficulty of translation mainly lies in the sentence connected with a pair of dashes. In example 7, the part "——*eye movements, prehension (reach and grasp), posture, locomotion, breathing, and speech*—" is the list of "movements classified according to function. In TT1， the translator translated "*—eye movements, prehension (reach and grasp), posture, locomotion, breathing, and speech—many of these functions are subserved by overlapping groups of muscles*." into"*——眼球运动、前视（伸手和抓握）、姿势、运动、呼吸和说话——但是这些功能中有不少共同参与的肌肉群*", retaining the double dashes and causing semantic interruption.

As mentioned above, when double dashes are only used to connect two parallel structures, we should adopt omission, adjust the word order and add logical connectives appropriately according to the context of the translated text and Chinese writing habits, so as to retain the logical connecting function of the double dashes in the original sentences. In example 7, the double dashes are used to connect the two parallel structures, namely, "*Although movements are often classified according to function*" and "*many of these functions are subserved by overlapping groups of muscles*". If the part "——*eye movements, prehension (reach and grasp), posture, locomotion, breathing, and speech—*" is omitted, the key meaning of the sentence would not be changed because that part only plays a role of adding the specific classification of movements. Therefore, in TT2, double dashes were converted into a colon and added a word "*为*" to connect them, conforming to Chinese writing habits and offering fluent translation.

Example 8:

ST: The plot shows the variability in the motion of the subjects* arm movements as the standard deviation of the extent of movement versus average speed (for each of three movement starting points and three movement times, giving nine data points).

TT1: 下图显示了受试者*手臂运动的变异性，即运动幅度与平均速度的标准偏差（运动幅度与平均速度的标准偏差，其中包括 3 个运动起点和 3 个运动时间）。

TT2: 下图的 9 个数据点，即运动幅度与平均速度的标准偏差，其中包括 3 个运动起点和 3 个运动时间。这 9 个数据点显示了受试者*手臂运动的变异性。

Analysis:

In example 8, the primary challenge in translation is associated with the translation of parentheses. In this example, the part "*(for each of three movement starting points and* *three movement times, giving nine data points)*" is used to further explain the data showed in the plot. In TT1, the translator translated "***(****for each of three movement starting points and three movement times, giving nine data points****)***" into"（*运动幅度与平均速度的标准偏差，其中包括 3 个运动起点和 3 个运动时间*）", which would puzzle the target readers because of the ambiguity of the data point.

As previously stated, English punctuation marks may be transformed into different forms in Chinese to preserve the original message. In example 8, parenthesis is used for sentence additions and it can be converted into other forms in Chinese to convey original message. Therefore, in TT2, the translator converted parenthesis into "*，即*"and adding "*这 9 个数据点*" to make the translation logical and clarify the information of the content in the parenthesis. In TT2, the translation not only reflects the real meaning of the source text but also embodies the inherent logic, achieving fluency and clarity.

Example 9：

ST：When the hand moves in the direction of the forearm **<u>(moving both arm and forearm)</u>**, inertia is two to three times greater than when the hand moves perpendicular to the forearm **<u>(moving the forearm alone).</u>**

TT1：当手沿前臂方向移动时**<u>（同时移动手臂和前臂）</u>**，惯性比手垂直于前臂移动时**<u>（仅移动前臂）</u>**大 2 到 3 倍。

TT2：当手沿前臂方向**<u>同时移动手臂和前臂</u>**时，惯性比**<u>手垂直于前臂移动</u>**时大 2 到 3 倍。

Analysis：

In example 9, translation challenge is primarily centered around the translation of parentheses in neuroscience passage. In this example, the parts "*(moving both arm and forearm)*" and "*(moving the forearm alone)*" are used to add the condition information. In TT1, the translator translated "*(moving both arm and forearm)*" *and* "*(moving the forearm alone)*" into"*(同时移动手臂和前臂）*" and "*(仅移动前臂)*", which would puzzle the target readers because of the interruption of the parentheses.

As previously discussed, it is possible that English punctuation marks are converted into other forms in Chinese to convey original message. In example 9, parenthesis is used for sentence additions and it can be converted into other forms in Chinese to convey original message. Therefore, in TT2, the translator omitted the parenthesis and translated the part "*(moving both arm and forearm)*" into "*同时移动手臂和前臂*" to make the translation concise. Besides, the translator omitted the part "(*moving the forearm alone*)" because it is obvious that it is impossible for the arm to move when it is perpendicular to the forearm. Therefore, the translator omitted the redundant information. In TT2, the translation not only manifests the implicit meaning of the source text but also embodies the inherent logic, resulting in a rendition that is both fluent and clear.

Example 10:

ST: With feedback control the desired and sensed states are compared **(at the comparator)** to generate an error signal, which helps shape the motor command.

TT1: 在反馈控制中，预期状态和感应状态**（在比较器中）**进行比较，以产生误差信号，从而形成电机指令。

TT2: 在反馈控制中，预期状态和感知状态**通过比较器**进行比较，以产生误差信号，从而形成电机指令。

Analysis:

In example 10, the difficulty of translation mainly lies in the translation of parentheses in neuroscience passage. In this example, the part "*(at the comparator)*" is used to explain the means of experiment. In TT1, the translator translated "*(at the comparator)*" into"（*在比较器中*）", which would cause reading interruption because of the parentheses.

As mentioned above， it is plausible that English punctuation marks are transformed into different forms in Chinese to preserve the original message. In this example, parenthesis is used for sentence additions and it can be converted into other forms in Chinese to convey original message. Consequently, in TT2, the translator omitted the parenthesis and added "*通过*" to manifest the implicit meaning of the content in parenthesis, improving the fluency of the translation. In TT2, the translation not only conveys the authentic meaning of the source text but also maintains the inherent logic, achieving a rendition that is both fluent and clear.

3.2.2 Converting Passive Voice into Active Voice in the Passage of Neuroscience

Due to the differences between the English and Chinese languages, the passive voice often fails to maintain its original linguistic structure and form when translated into Chinese because Chinese like to narrate things from the point of view of the giver while the British and American like to narrate things from the point of view of the receiver(任丁，1990). Therefore, when translating the passive voice, the first thing to consider is to translate it into an sentence with active voice. A common sentence pattern in Chinese is the sentences connected by “把”. In modern Chinese, there is a special grammatical structure called disposition. In terms of formal structure, it uses a prepositional verb “把”to bring the object in front of the verb. In terms of meaning, it is a purposeful action of the subject, expressing an initiative（王力 1958：26）. Therefore, when translating some passive voice, we can consider translating it as a “把” sentence according to its characteristics and application context.

“Translations should, as far as possible, use forms of speech that are pleasing to the recipients of the translation and that correspond to the expressive conventions of the target language.”（谭载喜，1984：79）. The passive voice is prevalent in scientific and technical texts. Newmark's communicative translation strategy for scientific and technical texts pays more attention to readers' understanding and acceptance. When translating, Chinese expressions are used to focus on the “person”, which can be the translator or the reader. When translating, one can either translate English passive sentences into Chinese sentences that are active in form but passive in meaning, or translate them into Chinese sentences that are completely active.

Example 11:

ST: How do sensorimotor transformations generate movement to a desired location? For a person to reach toward an object, **<u>sensory information about the target's location must be converted into a sequence of muscle actions</u>** leading to joint rotations that will bring the hand to the target.

TT1: 感觉运动转换是如何产生运动到所需位置的？对于一个人来说，要想把手伸向一个物体，**关于物体位置的感觉信息必须被转化为一连串的肌肉动作**，经过关节旋转，最终使得手能够准确地触及目标物体。

TT2: 感觉运动转换是如何让运动最终达到所需位置的？对于一个人来说，要想把手伸向一个物体，**他必须把关于物体位置的感觉信息转化为一连串的肌肉动作**，经过关节旋转，最终使得手能够准确地触及目标物体。

Analysis:

In example 11, the difficulty of translation mainly lies in the translation of passive voice, which needs to be converted into active voice to conform to Chinese expressions. In TT1, the translator translated "*sensory information about the target's location must be converted into a sequence of muscle actions*" into "*关于物体位置的感觉信息必须被转化为一连串的肌肉动作*", which lacks fluency and does not adhere to typical Chinese expression patterns.

As previously noted, "*被*" is possible to be used to express passive voice in translation. However， active voice are more often used in Chinese expressions. In example 11, the part "*sensory information about the target's location must be converted into a sequence of muscle actions leading to joint rotations that will bring the hand to the target*" is a sentence with passive voice. In TT2, the translator translated it into a sentence connected by "*把*" and added the subject "*他*" to conform to Chinese expression habits and achieve fluency. In TT2, the translation not only maintains the core idea of the original text but also resonates with the psychological and cultural inclinations of the target audience, thereby enhancing the readability and fluency of the translation.

Example 12:

ST: This and the straightness of hand paths mean that the extent of a movement **is planned** before the movement is initiated, and the movement **is generated** in a feedforward manner.

TT1: 这一点以及手部路径的直线性意味着，运动范围在运动开始之前就已**被规**

划好，并**被以**前馈方式**产生**。

TT2: 这一点和手部路径的直线性意味着，运动范围在运动开始之前就已经**规划**好了，并**通过**前馈方式**产生的**。

Analysis:

In example 12, the translation challenge is primarily associated with the conversion of passive voice into active voice to align with Chinese expression conventions. In TT1, the translation lacked fluency and did not conform to the habit of Chinese expression.

As previously noted, "*被*" are possible to be used to express passive voice in translation. However, active voice is more often used in Chinese expressions. In example 13, the parts "*is planned*" and "*is generated*" are the expressions with passive voice. In TT2, the translator translated them into "*规划*"and "通过……*产生*"to conform to Chinese expression habits and achieve fluency. In TT2, the translation not only mirrors the core idea of the original text but also resonates with the psychological and cultural inclinations of the target audience, thereby improving the readability and fluency of the translation.

Example 13：

ST: A repertory of movement schemas is the result of a process in which all possible ways of moving **are ranked** and the best **is selected.**

TT1：运动模式汇编是一个过程的结果，在这个过程中，所有可能的运动方式都将**在排列清单中**，并从中选择最好的。

TT2：运动模式汇编是一个过程的结果，在这个过程中，**大脑会排列出**所有可能的运动方式，并从中选择出最好的。

Analysis：

In example 13， the translation difficulty is primarily attributed to the conversion of passive voice into active voice to align with Chinese expression conventions. The translation in TT1 exhibited a lack of fluency and did not adhere to the habits of Chinese expression.

As previously mentioned, active voice are more often used in Chinese expressions. In this example, the part "*all possible ways of moving are ranked and the best is selected*" is the expression with passive voice. In TT2, the translator added the subject "*大脑*" to conform to Chinese expression habits and achieve fluency. In TT2, the translation not only reflects the core idea of the original text but also aligns with the psychological and cultural inclinations of the target audience, thereby improving the readability and fluency of the translation.

3.2.3 Adjusting the Order of Adverbial Modifier in the Passage of Neuroscience

There are some adverbial modifiers appearing in the source text which are difficult to be translated. Therefore, the translator adjusted the order of sentences to handle these difficulties. Chinese seldom puts the accusative between the subject and the predicate or at the end of the sentence, but usually places it before the subject or clause (赵小东, 2018:131-133). English expressions often place the semantic center of gravity at the beginning of the sentence, and then discuss the relevant situation, with a clear structure and hierarchy(常玉田, 2008). Also， English sentence structure mostly puts the semantic center of gravity at the beginning of the sentence, i.e., the important information is mostly reflected in the front, and the secondary information is mainly in the back. While Chinese largely follows the reverse order method, i.e., from big to small, from heavy to light, from far to near, English largely follows the sequential method. Specifically, in view of the differences between Chinese and English expressions, English sentences tend to put "result" and "after" at the beginning of the sentence in causal and sequential relationships, while Chinese sentences tend to put "cause" and "first" at the beginning of the sentence in causal and sequential relationships, which is different.

Example 14:

ST: <u>These internal representations have no intrinsic value and are behaviorally meaningful</u> only when used to guide movement, **<u>whether foraging for food or attracting a waiter's attention.</u>**

TT1:<u>这些内部表征没有内在价值，</u>只有在用于指导运动时才具有行为意义，**<u>无</u>**

论是觅食还是吸引服务员的注意。

TT2: 无论是在觅食还是吸引服务员注意力方面，这些内部表征皆无内在价值，只有在用于指导运动时才有行为意义。

Analysis:

In example 14, the primary challenge in translation is the rendering of the adverbial modifier. In this example, the part "*whether foraging for food or attracting a waiter's attention*" is the adverbial modifier that expresses conditions, while "*These internal representations have no intrinsic value and are behaviorally meaningful*" are the central part. In TT1, the translator translated the sentences without adjusting their order, which might puzzle the target readers and cause reading interruption.

As mentioned above, Chinese syntax typically avoids placing the accusative directly between the subject and the predicate or at the end of the sentence, opting instead for positions prior to the subject or clause. Adverbial modifiers are commonly positioned before the main clause, with postpositional use being less common. Therefore, in TT2, the translator placed "*whether foraging for food or attracting a waiter's attention*" before "*These internal representations have no intrinsic value and are behaviorally meaningful*" to conform to the Chinese expression habits. This adjustment in TT2 not only enhanced fluency but also conformed to the linguistic habits of Chinese expression.

Example 15:

ST： First, the hand tends to follow roughly a straight path, **although significant curvature is observed for certain movements, particularly vertical movements and movements near the boundaries of the reachable space.**

TT1： 首先，手的运动轨迹大致呈直线，但某些运动，尤其是垂直运动和接近可触及空间边界的运动，会出现明显的弯曲。

TT2： 首先，虽然我们能在某些运动，特别是垂直运动和靠近可及空间边界的运动中，观察到明显的弯曲，但是，手的运动轨迹大致呈直线。

Analysis:

In example 15, the difficulty of translation mainly lies in the translation of adverbial modifier. In this example, the segment "*although significant curvature is observed for certain movements, particularly vertical movements and movements near the boundaries of the reachable space*" is the adverbial modifier that expresses concession, while "*the hand tends to follow roughly a straight path*" are the central words. In TT1, the translator translated the sentences without adjusting their order, which might puzzle the target readers and cause reading interruption.

As mentioned above, Chinese seldom puts the accusative between the subject and the predicate or at the end of the sentence, but usually places it before the subject or clause. Adverbial modifier is usually placed before the central words, and postposition is rare. Therefore, in TT2, the translator placed "*although significant curvature is observed for certain movements, particularly vertical movements and movements near the boundaries of the reachable space*" before "*the hand tends to follow roughly a straight path*" to conform to the Chinese expression habits. In TT2, the order of sentences was adjusted to achieve fluency and conform to the habit of Chinese expressions.

Example 16：

ST： **Although reflexes are highly adaptable to changes in behavioral goals, mainly because several different circuits exist to connect sensory and motor neurons,** they cannot be directly controlled voluntarily.

TT1： **尽管反射对行为目标的变化有很强的适应性，主要是因为存在几个不同的电路来连接感受器和运动神经元，**它们仍不能直接由自主控制。

TT2： **由于存在几个不同的电路来连接感受器和运动神经元，因此，尽管反射对行为目标的变化有很强的适应性，**它们仍不能直接由自主控制。

Analysis：

In example 16, the translation challenge is primarily associated with the rendering of the adverbial modifier. In this example, the segment "*mainly because several different circuits exist to connect sensory and motor neurons*" is the adverbial modifier that expresses cause, while "*mainly because several different circuits exist to connect sensory and motor neurons*" and "*they cannot be directly controlled voluntarily*" are closely related. In TT1, the translator translated the sentences without adjusting their order, which would puzzle the target readers and cause focus ambiguity.

As previously discussed, English sentences tend to put “result” and “after” at the beginning of the sentence in causal and sequential relationships, while Chinese sentences tend to put “cause” and “first” at the beginning of the sentence in causal and sequential relationships. In this example, in TT2, the translator placed “*mainly because several different circuits exist to connect sensory and motor neurons*” before“ a*lthough reflexes are highly adaptable to changes in behavioral goals*” and translated “*because*” into “*由于*”, transferring the focus on the conclusion following the causative clause to conform to the Chinese expression habits. This adjustment in TT2 not only enhanced fluency but also clarified the logical focus of the text.

3.2.4 Dividing Long Sentences into Short Sentences in the Passage of Neuroscience

Sentences in scientific and technological texts contain strong logic, which inspired the translator to carefully analyze the logic in sentences to understand real meaning lest he should make obscure or even false translation (徐晓晔等, 2019:6). By adhering to the concepts of articulation and coherence, the translator is able to achieve a deeper understanding of the discourse characteristics of the source language and the communicative intent. This, in turn, enables the translator to structure the translation more effectively during the stages of transformation and re-creation, ensuring that it resonates naturally with the target language’s expression norms. Consequently, the translation can be rendered to flow as smoothly and authentically as a well-crafted original (郭建中, 2007:1-6).

In some English long sentences, the relationship between the main clause and the subordinate clause or modifying part is not close, while Chinese often has the habit of using short sentences to express the idea. So, it is useful to translate English subordinate clauses and modifying parts of a long sentence into Chinese short sentences (于建平, 2000:14-16). Division is used to cut them into short sentences in E-C translation. In addition, in contrast to English, when Chinese sentences unfold in a logical order, they tend to start with the cause or condition, followed by the result, (顾晓波, 2015:38-41).

Example 17:

ST: An internal model that represents the causal relationship between actions and their consequences is called a forward model because it estimates future sensory inputs based on motor outputs.

TT1：表示行动及其后果之间因果关系的内部模型被称为前向模型因为它根据运动输出来估计未来的感官输入。

TT2: 由于它根据运动输出估计未来的感觉输入，表示行动和其后果之间因果关系的内部模型被称为前向模型。

Analysis:

In example 17, the difficulty of translation mainly lies in the translation of long sentences, a common feature in English compared to the shorter, more concise sentences preferred in Chinese. In TT1，In TT1, the translator directly converted the lengthy English sentence into a similarly long Chinese sentence, an approach that lacks naturalness and may not align with Chinese stylistic norms.

As mentioned above, when translating from English to Chinese, we can use the translation method of division to cut English long sentences into short sentences to conform to the expression habits of Chinese. In addition， when Chinese sentences unfold in a logical order, they tend to start with the cause or condition, followed by the result. Therefore, in TT2 the long English sentence was divided into two short Chinese sentences and the causal clause was put at the beginning to achieve cohesion and coherence. In TT2, the internal logic of the passage is clarified with dividing the long sentence and adding some conjunctions.

Example 18:

ST: Thus, a copy of a descending motor command acting on the sensorimotor system is passed into a forward model that acts as a neural simulator of the musculoskeletal system moving in the environment.

TT1: 因此，作用于感觉运动系统的降序运动指令副本会被传递到前向模型中而前向模型则是肌肉骨骼系统在环境中运动的神经模拟器。

TT2: 因此，一个作用于感觉运动系统的下降运动指令的副本被传入一个前向模型，该模型作为肌肉骨骼系统在环境中运动的神经模拟器。

Analysis:

In example 18, the primary challenge in translation is attributed to the processing of long sentences. In TT1, the translator's approach involved a direct conversion of the protracted English sentence into a similarly protracted Chinese sentence, an approach that fails to align with the naturalness expected in Chinese language expression.

As mentioned above, when translating from English to Chinese, we can use the translation method of division. Therefore, the long English sentence was divided into two short Chinese sentences and the expression “*该模型*” was added to connect them. This segmentation of the long sentence, further enhanced by the inclusion of appropriate conjunctions, has effectively clarified the internal logic of the passage in TT2, resulting in a more coherent and linguistically appropriate translation.

Example 19:

ST： <u>**Although we may be aware of the intent to perform a task or of planning certain sequences of actions and at times are aware of deciding to move at a particular moment,**</u> movements generally seem to occur automatically.

TT1：<u>**尽管我们可能意识到执行一项任务的意图或计划某些行动的顺序而且有时也意识到决定在某一特定时刻移动**</u>，但运动通常似乎是自主发生的。

TT2：<u>**尽管我们可能意识到执行一项任务的意图或计划某些行动的顺序，有时也意识到决定在某一特定时刻移动**</u>，但运动通常似乎是自主发生的。

Analysis：

In example 19, the translation challenge is primarily situated in the realm of long sentence translation. English is characterized by its use of extended sentences, in contrast to the preference for succinctness in Chinese. I In TT1, the translator's method consisted of directly translating the lengthy English sentence into a similarly lengthy Chinese sentence, an approach that fell short of achieving naturalness in the target language.

As previously discussed, a division strategy can be effectively employed when translating English into Chinese, involving the splitting of long English sentences into shorter Chinese ones to better correspond with Chinese syntactic norms. Therefore, in TT2, this strategy was applied, dividing the protracted English sentence into two brief Chinese sentences. By doing so, the internal logic of the passage was delineated, and the coherence of the text was enhanced through the addition of appropriate conjunctions in TT2.

Chapter 4 Reflection

The completion of a translation practice should not stop at the formation of a translation, but to reflect and summarize the process of translation practice. Reflection is to examine oneself, and only by understanding one's own “knowledge” and “ignorance” can one make up for one’s shortcomings and make a better translation in the next practice. Only when we know what we “know” and “don't know” can we make up for our shortcomings in the next practice, make better translations, and improve ourselves. In the translation project, the translator mainly completed the translation through literature study, expert guidance and group study. Through these methods, she made the following summary of this translation practice, including four aspects: post-translation review, translation revelation, gains and limitations.

4.1 Proofreading

Detailed proofreading is an indispensable part of the translation process. As the translation practice is long and contains contents of certain specialized fields, it is inevitable that there will be certain subjectivity or mistakes in the translation process, therefore, after completing the translation, the translator carried out three rounds of proofreading in order to improve the quality of the translation in the end, and the specific proofreading process consisted of three rounds: self-revision, in-group revision, and tutor proofreading.

Firstly, self-revision was carried out, mainly checking whether there were any obvious mistakes in the details of the translation, such as the use of punctuation, font size, whether there were mistranslations and omissions, and whether there was inaccurate verification. Secondly, the group members carried out group revision, which paid attention to the readability of the translations. The group members read through the translations without looking at the original text, marking the points that were difficult to be understood or the points where there was room for modification, and then reviewing the translations in comparison with the original text, brainstorming, and discussing the translations. Then the group members made a translation review with the original text to discuss the translation problems and improve the translation quality. Finally, the tutor made a review, mainly suggesting modifications to some complex sentences and important and difficult problems, and at the same time annotating the problems of the translation. On this basis, the translator polished and improved the translation, and finalized it through repeated revisions.

4.2 Gains

Translation is a continuous learning process. Before translation, we can learn a great deal of knowledge; in the process of translation, we can apply various translation methods and techniques we have learned; after translation, we must review the whole translation process and analyze the gains and losses.

First of all, the translator recognizes the necessity of pre-translation preparation, which includes the understanding of background knowledge, building glossaries as well as finding suitable translation tools. Understanding the background knowledge to achieve a complete understanding of the original text and finding suitable translation tools to improve the quality and speed of translation. In addition, tools for checking terminology must be authoritative and glossaries need to be kept up to date. In the process of translation practice, after the material was determined, the translator actively consulted relevant information according to the content of the original text, read the parallel text, analyzed the text, and determined the proper noun. Although it took a long time, it is helpful for the translator to understand the content of the translation practice and to speed up the process of translation in the later stage.

Secondly, the importance of post-translation proofreading should not be neglected. Detailed proofreading is an indispensable part of the translation process. In the case of English to Chinese translation, due to the formal constraints of the shell of the source language, it is inevitable that awkward or unorthodox expressions might exist in the Chinese translation. In the process of proofreading, the thinking might be restricted, so three processes are carried out: self-proofreading, group proofreading and tutor proofreading. New problems might be found in each process of proofreading, so the translations should be revised, embellished and perfected before the final draft is completed. In one word, the diversified proofreading can make the translations more reliable.

Finally, translators need to think of solutions to cope with unfavorable factors in order to do better. English scientific and technical texts have a strong logical structure as well as more difficult terminology, which can cause difficulties in understanding. For logical structures, translators need to analyze them step by step. I recognize the importance of mastering different translation strategies. Translators need to master various translation strategies, such as omission and transcription, in order to cope with the important and difficult points in translation. Translation methods and techniques are difficult to be exhaustive, but they can provide general translation directions and principles. Flexible use of translation theories, methods and techniques will bring better translation results.

4.3 Limitations

First of all, the translator is not a professional cognitive neurology learner, and cannot grasp all the relevant knowledge in a short time, and still lacks in background knowledge. Although the translator read the relevant materials, due to the limited time, she only focused on the relationship between the nervous system and movement. As the nervous system is connected by different organs, each of which is linked to the other, focusing on only one part is not conducive to her understanding of the transmission patterns between the cells of the nervous system and other parts of the text. As a result, her understanding and translation might not be completely accurate. Secondly, the translation ability needs to be improved. The translator has not fully mastered all the translation skills. She needs to continue to practice and needs to study various translation theories in depth and link the theories well with translation practice.

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Appendix

Appendix I: Glossary

Allocentric coordinates	分配中心坐标
Amplitudes	振幅
Angular velocity	角速度
Arc	弧线
Ballistic	弹道
Brain stem	脑干
Cartesian coordinates	笛卡尔坐标
Central neurons	中枢神经元
Central Nervous System	中枢神经系统
Closed-loop systems	闭环系统
Cranial nerves	颅神经
Curvature	曲率
Cutaneous receptors	皮肤感受器
Dorsal roots	脊髓根
Dorsal stream	背侧信息流
Egocentric coordinate systems	自我中心坐标系
Elevation and azimuth	仰角和方位角
Efferent signal	感知信号
Efference Copy (Corollary Discharge)	感知副本(伴随放电）
Error Correction in Movement	运动误差修正
Feedforward Processes	前馈处理
Forward Model	正向模型

Feedback Control	反馈控制
Fitts’s law	菲茨定律
Geometric parameters	几何参数
Golgi tendon organs	高尔基腱器官
Grip force	握力
High-level cognitive centers	高级认知中枢
Inertia	惯性
Instantaneous values	瞬时值
Inverse dynamic transformation	反动态转换
Inverse Model	逆模型
Internal Models	内部模型
Internal Representations ("Neural Maps")	内部表征（神经元映射）
Joint	关节
Kinematic	运动学的，运动学上的
Kinetic	活跃的，运动的
Kinematic Information	运动信息
Mechanoreceptors	机械性刺激感受器
Microelectrodes	微电极
Microneurography	微神经电图
Movement primitive	运动基元
Movement vector	运动矢量
Motor Commands	运动指令
Muscle Spindles	肌梭；肌纺锤
Motor Learning	运动学习
Motor Equivalence	运动等效性
Oscillatory tremor	振荡性震颤
Pacinian corpuscles	帕氏体
Path curvature	路径曲率
Peripheral sensory system	外周感觉系统

Power law relation	幂律关系
Proprioception	本体感觉
Prediction in Motor Control	运动控制预测
RA2 fibers	快适应感受器二类纤维
RA2 signals	快适应感受器二类信号
Retina	视网膜
Sensorimotor	感觉运动
Sensorimotor loop	感觉运动环路
Sensorimotor system	感觉运动系统
Sensory axons of the peripheral nerve	周围神经感觉轴突
Sensory feedback	感觉反馈
Sensory signals	感觉信号
Spherical coordinates	球面坐标
Spherical polar coordinates	球极坐标
Sensory Feedback Delays	感觉反馈延迟
Stereotypical Patterns	常规范型
Stimulus receptors	刺激受体
Stylus	测针
Tactile sensations	触觉
Tendon reflexes	肌腱反射
Tendon-jerk reflex	肌腱抽搐反射
The two-thirds power law	三分之二幂律
Torques	扭矩
Trajectories	运动轨迹
Velocity profiles	速度曲线
Ventral stream	腹侧流
Vestibular labyrinth	前庭迷宫
Vestibulo-ocular reflex	前庭-眼动反射
Visual cortex	视觉皮层

Appendix II：The Source Text and Target Text

Source Text	**Target Text**
The Organization and Planning of Movement	运动的组织和计划
Motor Commands Arise Through Sensorimotor Transformations	运动指令通过感觉运动转换而起始
The Central Nervous System Forms Internal Models of Sensorimotor Transformations	中枢神经系统形成感觉运动转换的内部模型
Movement Inaccuracies Arise from Errors and Variability in the Transformations	**运动误差**来自于转换中的误差和变化
Different Coordinate Systems May Be Employed at Different Stages of Sensorimotor Transformations	不同阶段中的感觉运动转换所运用的坐标系统不同
Stereotypical Patterns Are Employed in Many Movements	许多运动都采用传统模式
Motor Signals Are Subject to Feedforward and Feedback Control	运动信号受制于前馈和反馈控制
Feedforward Control Does Not Use Sensory Feedback	前馈控制不使用感觉反馈
Feedback Control Uses Sensory Signals to Correct Movements	反馈控制利用感觉信号纠正运动
Prediction Compensates for Sensorimotor Delays	预测可以弥补感觉运动的延迟行动
Sensory Processing Is Different for Action and Perception	在动作和感知方面，感觉的处理有所不同
Motor Systems Must Adapt to Development	运动系统必须适应发展和经验

and Experience	
Motor Learning Involves Adapting Internal Models for Novel Kinematic and Dynamic Conditions	涉及新型运动学和动力学条件调整内部模型的运动学习
Kinematic and Dynamic Motor Learning Rely on Different Sensory Modalities	运动学和动力学运动学习依赖于不同的感觉模式
An Overall View	本章小结
In the proceeding part of this book we considered how the brain constructs internal representations of the world around us. **These internal representations have no intrinsic value and are behaviorally meaningful only when used to guide movement, whether foraging for food or attracting a waiter's attention.** Thus, the ultimate function of the sensory representations is to shape the actions of the motor systems. Sensory representations are the framework in which the motor systems plan, coordinate, and execute the motor programs responsible for purposeful movement.	在本书的前一部分，我们思考了大脑如何构建我们周围世界的内部表征。**无论是在觅食还是吸引服务员注意力方面，这些内部表征皆无内在价值，只有在用于指导运动时才有行为意义。**因此，感觉表征的最终功能是塑造运动系统的行动。感觉表征是一种运动系统计划、协调和执行负责有目的运动的运动程序框架。
In this part of the book, we describe the principles of motor control that allow the brain and spinal cord to maintain balance and posture; to move our body, limbs, and eyes; and to communicate through speech and gesture.	在本书的这一章节，我们描述了运动控制的原理，使大脑和脊髓能够保持平衡以及维持姿势；移动我们的身体、四肢和眼睛；并通过语言和手势进行交流
Although movements are often classified according to function—eye movements, prehension (reach and grasp), posture, locomotion, breathing, and speech—many of these functions are subserved by	**按照功能，运动通常可以分为：眼球运动、前视（伸手和抓握）、姿势、运动、呼吸和说话。然而，这些功能中有不少共同参与**

overlapping groups of muscles. In addition, the same groups of muscles can be controlled voluntarily, rhythmically, or reflexively. For example, the muscles that control respiration can be used to take a deep breath voluntarily before diving under water, to breathe automatically and rhythmically in a regular cycle of inspiration and expiration, or to act reflexively in response to a noxious stimulus in the throat, producing a cough.	**的肌肉群。**此外，相同的肌肉群可以自主地、有节奏地或反射性地控制。例如，控制呼吸的肌肉可以用来在潜入水中前自主深呼吸，在有规律的吸气和呼气循环中自主把握节奏呼吸，或者在喉咙受到有毒刺激时通过咳嗽做出反应。
Voluntary movements are those that are under conscious control by the brain. Rhythmic movements can also be controlled voluntarily, but many such movements differ from voluntary movements in that their timing and spatial organization is to a large extent controlled autonomously by spinal or brain stem circuitry. Reflexes are stereo-typed responses to specific stimuli that are generated by simple neural circuits in the spinal cord or brain stem. **Although reflexes are highly adaptable to changes in behavioral goals, mainly because several different circuits exist to connect sensory and motor neurons, they cannot be directly controlled voluntarily.**	自主运动是指那些由大脑控制的科学运动。节奏运动也可以通过自主控制达成，但许多这样的运动与自主运动不同，它们的时间和空间组织在很大程度上是由脊柱或脑干电路自动控制。反射是对特定刺激的定型反应，由脊髓或脑干的简单神经回路产生。**由于存在几个不同的电路来连接感受器和运动神经元，因此，尽管反射对行为目标的变化有很强的适应性，它们仍不能直接由自主控制。**
In this chapter we focus on voluntary movements, using arm and hand movements to illustrate principles of sensorimotor control. Reflexes and rhythmic movements are discussed in detail in Chapters 35 and 36.	在这一章中，我们重点讨论自主运动，用手臂和手的运动来说明感觉运动控制的原理。反射和节奏运动将在第 35 章和第 36 章中详细讨论。

Conscious processes are not necessary for moment- to-moment control of movement. **Although we may be aware of the intent to perform a task or of planning certain sequences of actions and at times are aware of deciding to move at a particular moment, movements generally seem to occur automatically.** We carry out the most complicated movements without a thought to the actual joint motions or muscle contractions required. The tennis player does not consciously decide which muscles to use to return a serve with a backhand or which body parts must be moved to intercept the ball. In fact, thinking about each body movement before it takes place can disrupt the player's performance.	有意识的过程对于运动的瞬间控制并非必要。**尽管我们可能意识到执行一项任务的意图或计划某些行动的顺序，有时也意识到决定在某一特定时刻移动，但运动通常似乎是自主发生的。**我们在进行最复杂的动作时，不会考虑实际的关节运动或肌肉收缩的需要。网球运动员不会有意识地决定用哪块肌肉来回击反手发球，或必须移动哪些身体部位来拦截球。事实上，在每一个身体动作发生之前思考，会扰乱球员的表现。
In this chapter we review the principles that govern the neural control of movement using concepts derived from behavioral studies and from computational models that are used both to understand the brain and to control the movements of robots. First, we look at how the brain transforms sensory inputs into motor outputs through a cascade of sensorimotor transformations. Second, we examine how sensory feedback can be used to correct errors that arise during movement. Finally, we see how motor learning allows us to improve our performance; to adapt to new mechanical conditions, as when using a tool; or to adapt to novel correspondences between sensory and motor events, for	在这一章中，我们回顾了支配运动的神经控制的原则，这些概念来自于行为研究和计算模型，这些模型用于理解大脑和控制机器人的运动。首先，我们研究了大脑是如何通过一连串的感测器转换将感觉输入转化为运动输出的。其次，我们研究如何利用感觉反馈来纠正运动中出现的错误。最后，我们看到运动学习如何改善我们的表现；适应新的机械条件，如使用工具时；或适应感觉和运动事件之间的新的对应关系，如学习使用电脑鼠标控制

example when learning to use a computer mouse to control a cursor.	光标时。
Motor Commands Arise Through Sensorimotor Transformations	运动指令通过感觉运动转换而起始
Motor outputs are neural commands that act on the muscles, causing them to contract and generate movement. These outputs are derived from sensory inputs in circuits that represent sensorimotor transformations. Sensory inputs include extrinsic information about the state of world as well as intrinsic information about our body. Extrinsic information, for example the spatial location of a target, can be provided by auditory and visual inputs. Intrinsic information includes both kinematic and kinetic information about our body.	运动输出是作用于肌肉的神经指令，使它们收缩并产生运动。这些输出来自代表感觉运动转换的电路中的感觉输入。感觉输入包括关于世界状态的外在信息以及关于我们身体的内在信息。外在信息，例如目标的空间位置，可以由听觉和视觉输入提供。内在信息包括关于我们身体的运动学和动力学信息。
Kinematic information includes the position, velocity, and acceleration of the hand, joint angles, and lengths of muscles without reference to the forces that cause them. Kinetic information is concerned with the forces generated or experienced by our body. These different forms of intrinsic information are provided by different sensors. For example, information about muscle lengths and their rate of change is provided mainly by muscle spindles, whereas Golgi tendon organs in the muscles and mechanoreceptors in our skin provide information about the force we are exerting.	运动学信息包括手的位置、速度和加速度、关节的角度和肌肉的长度，但不涉及它们的力量来源。运动学信息涉及我们身体产生的或经历的力。这些不同形式的内在信息是由不同的传感器提供的。例如，关于肌肉长度及其变化率的信息主要由肌肉主轴提供，而肌肉中的高尔基腱器官和皮肤中的机械感受器则提供我们所施加的力的信息。
Simple reflexes, such as a tendon-jerk reflex, involve a simple sensorimotor	简单的反射，如肌腱抽搐反射，涉及一个简单的感觉运动转换。

transformation: Sensory inputs cause motor output directly without the intervention of higher brain centers. However, voluntary movement requires multistage sensorimotor transformations. The involvement of multiple processing centers actually simplifies processing: Higher levels plan more general goals, whereas lower levels concern themselves with how these goals can be implemented.	感觉输入直接导致运动输出，不需要高级大脑中心的干预。然而，自主运动需要多阶段的感觉-运动转换。多个处理中心的参与实际上简化了处理过程。高级阶段的计划更多涉及总体目标，而低级阶段的计划则关注如何实现这些目标。
Such a hierarchy accounts for the fact that a specific motor action, such as writing, can be performed in different ways with more or less the same result. Handwriting is structurally similar regardless of the size of the letters or the limb or body segment used to produce it (Figure 33-1).	这种层次结构说明了这样一个事实，即一个特殊的运动动作，如书写，可以用不同的方式进行，而结果却大致相同。无论字母的大小或用于书写的肢体或身体部位有何不同，笔迹在结构上却是相似的（图 33-1）
This phenomenon, termed motor equivalence, suggests that purposeful movements are represented in the brain trajectory, the time course over which these positions will be covered, and thus the accelerations and speeds of the movement (Figure 33-2B).	这种现象被称为运动等效性，表明有目的的运动在大脑轨迹中得到体现，在这一时间过程中，这些位置将被覆盖，从而体现出运动的加速度和速度（图 33-2B）
In a hierarchical model of planning the goal can be expressed in kinematic terms, such as the desired positions and velocities of the hand, or in kinetic terms, such as the force exerted by the hand. Movement can be planned as an endpoint trajectory, a desired change in the configuration of the limb expressed in coordinates intrinsic to the	在计划的分层模型中，目标可以用运动学术语来表达，如手的理想位置和速度，或用运动学术语来表达，如手所施加的力。运动可以被规划为一个终点轨迹，即用肢体固有的坐标系表示的肢体配置的预期变化。

limb. Such a coordinate system could determine the change in joint angles or be based on a desired change in proprioceptive feedback. For example, the endpoint trajectory could be defined kinematically as the distance and direction the hand has to move to reach the target, as well as the speed along the path to the target.	这种坐标系统可以决定关节角度的变化，或基于本体感觉反馈的预期变化。例如，端点轨迹可以在运动学上定义为手到达目标的距离和方向，以及到达目标的路径上的速度。
Transformations can be expressed as changes in kinematic variables, such as the position of the hand and the joint angles that place the hand at that position. The calculation of an endpoint from a set of joint angles termed forward kinematic transformation, whereas abstractly rather than as sets of specific joint motions or muscle contractions. Such abstract representations of movement, able to drive different effectors, provide a degree of flexibility of action not practical with preset motor programs.	变换可以表示为运动学变量的变化，如手的位置和使手处于该位置的关节角度。从一组关节角度计算出的终点称为前向运动学转换，而不是抽象地计算出一组具体的关节运动或肌肉收缩。这种抽象的运动表示，能够驱动不同的效应器，提供了一定程度的行动灵活性，这在预设的运动程序中并不现实。
How do sensorimotor transformations generate movement to a desired location? **For a person to reach toward an object, sensory information about the target's location must be converted into a sequence of muscle actions leading to joint rotations that will bring the hand to the target.**	感觉运动转换是如何让运动最终达到所需位置的？**对于一个人来说，要想把手伸向一个物体，他必须把关于物体位置的感觉信息转化为一连串的肌肉动作，经过关节旋转，最终使得手能够准确地触及目标物体。**

First, the target is localized in space relative to some part of the body such as the head or arm (egocentric space). Several sources of information are combined in this process. For example, the location of the target relative to the head is computed from the location of the target on each retina together with the direction of gaze of the eyes (Figure 33-2A). A person also needs to know the initial location of his hand or the tip of the tool that he wishes to place on the target (the end- effector or endpoint). The initial location of the endpoint can be estimated by combining visual inputs, proprioceptive signals, and tactile sensations, each of which can provide location information. Once the current configuration of the arm and the location of the target are calculated, a movement can be planned. A plan typically has to specify both a particular path, the successive spatial positions of the endpoint, and also the calculation of a set of joint angles that can reach an endpoint is termed inverse kinematic transformation (Figure 33-2C). This transformation must take into account the geometric parameters of the arm, such as the lengths of the upper arm and forearm (recall that kinematics considers motion without reference to the forces that cause it). The motor system controls joint angle by activating muscles that produce torques (rotational forces) at the joint.	首先，目标在空间中相对于身体的某些部分，如头部或手臂（以自我为中心的空间）被定位。在这个过程中，有几个信息源被结合起来。例如，目标相对于头部的位置是根据目标在每个视网膜上的位置和眼睛的注视方向计算出来的（图 33-2A）。一个人还需要知道他的手或他希望放在目标上的工具顶端的初始位置（终端效应器或端点）。端点的初始位置可以通过视觉输入、本体感觉信号和触觉的结合来估算，每一种都可以提供位置信息。一旦计算出手臂的当前配置和目标的位置，就可以计划一个运动。一个计划通常既要指定一个特定的路径、终点的连续空间位置，也要计算一组可以到达终点的关节角度，这被称为逆运动学转换（图 33-2C）。这种转换必须考虑到手臂的几何参数，如上臂和前臂的长度（回顾一下，运动学考虑的是运动而不是引起运动的力）。运动系统通过激活在关节处产生扭力（旋转力）的肌肉来控制关节角度。
The action of motor commands on muscles	因运动指令对肌肉的作用而产生

that results in a set of angular positions and velocities is known as the forward dynamic transformation. The term "dynamic" refers to the forces required to cause motion. However, to generate a desired joint angle trajectory the system must convert kinematic parameters into motor commands. That is, the system must calculate the torques at each joint necessary to achieve the motion and relate the force required to cause this motion to the desired acceleration of the limb. This transformation is known as the inverse dynamic transformation (Figure 33-2D). In general, to cause any acceleration the forces applied must exceed any resistive forces arising from the viscosity or stiffness of the limb, from gravity, and from external loads. The force not required to overcome the total resistive force will cause an angular acceleration, with the acceleration being dependent on the limb's inertia; the lower the inertia, the higher the acceleration.	的一组角度位置和速度变化，我们称之为前向动态转换。术语"动态"是指引起运动所需的力量。然而，为了产生一个理想的关节角度轨迹，系统必须将运动学参数转换为运动指令。也就是说，系统必须计算出实现运动所需的每个关节的扭矩，并将引起这一运动所需的力与肢体的预期加速度联系起来。这种转换被称为反动态转换（图 33-2D）。一般来说，想要产生加速度，所施加的力必须超过由肢体的粘性或硬度、重力和外部负荷引起的任何阻力。不需要克服总阻力的力将引起角加速度，加速度取决于肢体的惯性；惯性越低，加速度越大。
Thus, through a series of sensorimotor transformations, sensory input is finally converted into muscle contractions that generate movement. Although we have described one possible series of transformations that can achieve a movement, the actual computations used by the central nervous system are still under active investigation.	因此，通过一系列的感觉运动转换，感觉输入最终转换为能引发运动的肌肉收缩。尽管我们已经描述了一系列能实现运动的可能转换，但中枢神经系统使用的实际计算仍在积极研究之中。
Movement planning	运动计划
cup	杯子

Inverse kinematics	逆运动学
Elbow angle trajectory	肘关节角度轨迹
Inverse kinematics	逆运动学
Shoulder angle trajectory	肩部角度轨迹
Elbow torque	肘部扭矩
Shoulder torque	肩部扭矩
The Central Nervous System Forms Internal Models of Sensorimotor Transformations	中枢神经系统形成感觉运动转换的内部模型
We know from cellular studies that the central nervous system contains internal representations ("**neural maps**") of the various sensory receptor arrays and the musculature. Experimental and modeling studies strongly suggest that the central nervous system also maintains internal representations that relate motor commands to the sensory signals expected as a result of movement.	我们从细胞研究中得知，中枢神经系统包含各种感觉受体阵列和肌肉组织的内部表征（“**神经元映射**”）。实验和建模研究强烈表明，中枢神经系统也保持着内部表征，将运动指令与预期的运动结果的感觉信号联系起来。
Given the fixed lengths of our limb segments, there is a mathematical relationship between the joint angles of the arm and the location of the hand in space. A neural representation of this relationship allows the central nervous system to estimate hand position if it knows the joint angles and segment lengths. The neural circuits that compute such sensorimotor transformations are examples of internal models (Box 33-1). Such neural representations may not exactly match true relationships because of structural differences (the models only approximate	鉴于我们肢体节段的固定长度，手臂的关节角度和手在空间的位置之间存在着一种数学关系。如果中枢神经系统知道关节角度和节段长度，那么这种关系的神经表征可以让它估算手的位置。计算这种感觉运动转换的神经回路是内部模型的例子（框 33-1）。由于结构上的差异（模型仅近似于关节角度和手部位置之间的真实关系）或模型参数上的错误（对节段长度的错误估算），这种神经

the true relationship between joint angles and hand position) or errors in the model's parameters (incorrect estimates of segment lengths).	表征可能与真实关系不完全匹配。
An internal model that represents the causal relationship between actions and their consequences is called a forward model because it estimates future sensory inputs based on motor outputs. A forward model anticipates how the motor system's state will change as a result of a motor command. **Thus, a copy of a descending motor command acting on the sensorimotor system is passed into a forward model that acts as a neural simulator of the musculoskeletal system moving in the environment.** This copy of the motor command is known as an **efference copy (or corollary discharge)** to signify that it is a copy of the **efferent signal** flowing from the central nervous system to the muscles. We will see later how such simulations can be learned and used in sensorimotor control.	**由于它根据运动输出估计未来的感觉输入，表示行动和其后果之间因果关系的内部模型被称为前向模型**。前向模型预计运动系统的状态将如何作为运动指令的结果而改变。**因此，一个作用于感觉运动系统的下降运动指令的副本被传入一个前向模型，该模型作为肌肉骨骼系统在环境中运动的神经模拟器**。这个运动指令的拷贝被称为**感知副本（或伴随放电）**，表示它是一个从中枢神经系统流向肌肉的**感知信号**的拷贝。我们将在后面看到这种模拟是如何被学习和用于感觉运动控制的。
An internal model that calculates motor outputs from sensory inputs is known as an inverse model. Such a model can determine what motor commands are needed to produce the particular movements necessary to achieve a desired sensory consequence.	从感觉输入计算运动输出的内部模型被称为逆向模型。这样的模型可以确定需要什么样的运动指令来产生必要的特定动作，以达到预期的感觉后果。
Forward and inverse models can be better understood if we place the two in series. If the structure and parameter values of each	如果我们把正向和反向模型放在一起串联，就可以更好地理解这两个模型。如果每个模型的结构

model are correct, the output of the forward model (the predicted behavior) will be the same as the input to the inverse model (the desired behavior)(Figure 33-3).	和参数值都是正确的，正向模型的输出（预测行为）将与反向模型的输入（期望行为）相同（图 33-3）。
Box 33-1 Internal Models	框 33-1 内部模型
The utility of numerical models in the physical sciences has a long history. Numerical models are abstract quantitative representations of complex physical systems. Some start with equations and parameters that represent initial conditions and run forward, either in time or space, to generate physical variables at some future state. For example, we can construct a model of the weather that predicts wind speed and temperature two weeks from now. In general, the algorithms and parameters of the model should lead to one correct answer.	数值模型在物理科学中的应用由来已久。数值模型是复杂物理系统的抽象量化表示。有些模型从代表初始条件的方程和参数开始，在时间或空间上向前运行，以产生未来某个状态的物理变量。例如，我们可以构建一个天气模型，预测两周后的风速和温度。一般来说，模型的算法和参数应该最终产生一个正确的答案。
Other models start with a state, a set of physical variables with specific values, and operate in the inverse direction to determine what parameters in the system account for that state. When we fit a straight line to a set of data points, we are constructing an inverse model that estimates slope and intercept based on the equations of the system being linear. An inverse model may thus inform us how to set the parameters of the system to obtain desired outcomes.	其他模型从一个状态开始，即一组具有特定值的物理变量，并在反方向上操作，以确定系统中的哪些参数会造成这种状态。当我们将一条直线拟合到一组数据点上时，我们正在构建一个逆向模型，根据系统的线性方程来估计斜率和截距。因此，逆向模型可以告诉我们如何设置系统的参数以获得期望的结果。
Over the last 50 years, the idea that the nervous system has similar predictive models of the physical world to guide	在过去的 50 年里，神经系统中用类似物理世界的预测模型来指导行为的想法已经成为神经科学的

behavior has become a major issue in neuroscience. The idea originated in Kenneth Craik's notion of internal models for cognitive function. In his 1943 book, The Nature of Explanation, Craik was perhaps the first to suggest that organisms make use of internal representations of the external world:	一个重要问题。这个想法起源于肯尼斯-克雷克的认知功能内部模型的概念。在他 1943 年出版的《解释的本质》一书中，克雷克也许是第一个提出这个概念的人。
"If the organism carries a 'small-scale model' of external reality and of its own possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events in dealing with the present and future, and in every way to react in a much fuller, safer, and more competent manner to the emergencies which face it."	"如果有机体在其头脑中带有外部现实和自身可能行动的'小规模模型'，它就能够尝试各种备选方案，得出其中最好的结论，在未来情况出现之前作出反应，在处理现在和未来时利用过去事件的知识，并在各个方面以更全面、更安全、更有能力的方式对它所面临的紧急情况作出反应。"
In this view an internal model allows an organism to contemplate the consequences of current actions without actually committing itself to those actions.	在这种观点中，内部模型允许有机体考虑当前行动的后果，而不实际履行这些行动。
Considering the human body from the viewpoint of sensorimotor control, we should ask two fundamental questions. First, how can we generate actions on the system so as to control its behavior? Second, how can we predict the consequences of our actions?	从感觉运动控制的角度考虑人体，我们应该提出两个基本问题。首先，我们如何在系统上产生行动，以控制其行为？第二，我们如何预测我们行动的后果？
The central nervous system must exercise both control and prediction to achieve skilled motor performance. Prediction and control are two sides of the same coin, and	中枢神经系统必须同时进行控制和预测，运动得以熟练进行。预测和控制是一个硬币的两面，这

the two processes map exactly onto forward and inverse models. Prediction turns motor commands into expected sensory consequences, whereas control turns desired sensory consequences into motor commands.	两个过程正好映射到正向和反向模型上。预测将运动指令转化为预期的感觉后果，而控制将预期的感觉后果转化为运动指令。
Desired behavior	预期行为
Inverse model	逆向模型
Moror command	摩尔指令
Forward model	正向模型
Actual	实际行为
Predicted behavior	预测行为
Movement Inaccuracies Arise from Errors and Variability in the Transformations	**运动误差**来自于转换中的误差和变化
Motor control is often imprecise. Indeed, society celebrates those who can throw a dart into a small area of a board or hit a small white ball into a hole with a club. However, even the movements of the most skilled players show some degree of variability. In the 1890s the psychologist Robert Woodworth showed that fast movements are less accurate than slow ones. People slow their movements when accuracy is demanded. Inaccuracy can arise either from variability in the sensory inputs and motor outputs or from errors in the internal representations of this information.	运动控制往往是不精确的。的确，社会对那些能够将飞镖投进棋盘的一个小区域或用球杆将一个小白球打进洞的人表示赞赏。然而，即使是最熟练的选手，其动作也显示出一定程度的可变性。在 19 世纪 90 年代，心理学家罗伯特-伍德沃斯（Robert Woodworth）表明，相比慢速运动，快速运动的准确性较低。当准确性是其中一个要求时，人们会放慢动作。不准确可能来自于感觉输入和运动输出的变化性，或来自于这些信息的内部表征的错误。
An important component of sensorimotor	感知运动变化性的一个重要组成

variability is the intrinsic variability of our sensors and motor neurons because of fluctuations in their membrane potential. Because of these fluctuations, known as neural noise, the level of input signals required to trigger postsynaptic action potentials also varies. On the input side, neural noise limits the accuracy of estimates of the location of a target or limb (how near an estimate is to the true value) as well as their precision (how accurate the estimate is when repeated). On the output side, neural noise limits the accuracy and precision with which we contract our muscles. Moreover, the amount of noise in motor commands tends to increase with larger motor commands, limiting our ability to move rapidly and accurately at the same time. This increase in variability is caused by random variation in both the excitability of motor neurons and the recruitment of the additional motor units needed to produce increases in force.	部分是我们的传感器和运动神经元由于其膜电位的波动而产生的内在变化性。由于这些波动，即所谓的神经噪音，触发突触后动作电位所需的输入信号的水平也是不同的。在输入端，神经噪声限制了对目标或肢体位置估算的准确性（估算值与真实值的接近程度）以及它们的精确度（重复估算时的准确程度）。在输出方面，神经噪音限制了我们收缩肌肉的准确性和精确度。此外，运动指令中的噪音量往往随着较复杂运动指令而增加，限制了我们同时快速和准确运动的能力。这种变化性的增加是由运动神经元的兴奋性和为产生力的增加所需的额外运动单元的招募的随机变化引起的。
Incremental increases in force are produced by progressively smaller sets of motor neurons, each of which produces disproportionately greater increments of force (see Chapter 34). Therefore, as force increases, fluctuations in the number of motor neurons lead to greater fluctuations in force. The consequences of this can be observed experimentally by asking subjects to generate a constant force or a force pulse	力的递增是由逐渐变小的运动神经元组产生的，每个运动神经元产生的力的递增不成比例地大（见第 34 章）。因此，随着力的增加，运动神经元数量的波动会导致力的更大波动。通过要求受试者产生一个恒定的力或一个固定振幅的力脉冲，可以在实验中观察到这种后果。受试者不仅不

of fixed amplitude. Not only are subjects unable to maintain a constant force, but the variability of force also increases with the level of the force. Over a large range, this increase in variability is captured by a constant coefficient of variation (the standard deviation divided by the mean force). This dependence of variability on force corresponds to the increase in the variability of pointing movements with the average speed of movement. The decrease in the accuracy of movement with increasing speed is known as the speed-accuracy trade-off (Figure 33-4).	能保持恒定的力，而且力的可变性也随着力的水平而增加。在一个很大的范围内，这种变异性的增加被一个恒定的变异系数（标准偏差除以平均力）所捕获。这种变异性对力的依赖性与指向性运动的变异性随着平均运动速度的增加而增加相对应。随着速度的增加，运动的准确性下降，这被称为速度-准确性的权衡（图33-4）。
Errors can also arise from inaccuracy in the internal models that compute sensorimotor transformations. Neural representations of the musculature cannot easily capture the complex biomechanical properties of the musculoskeletal system, and this in turn significantly complicates the ability of the brain to compute accurate sensorimotor transformations. Indeed, the dependence of muscle force on motor command is itself highly complex. A model prescribing motion in a system with just a single joint must not only estimate the muscle force (or torque) but also take into account inertia (the mass resisting acceleration), viscosity (resistive forces proportional to velocity), stiffness (elastic forces proportional to displacement) produced by the muscles and tendons opposing movement, and gravity.	错误也可能来自计算感觉运动转换的内部模型的不准确。肌肉组织的神经表征不容易捕捉到肌肉骨骼系统的复杂生物力学特性，这反过来又使大脑计算准确的感觉运动转换的能力变得非常复杂。事实上，肌肉力量对运动指令的依赖性本身就非常复杂。在一个只有一个关节的系统中规定运动的模型不仅要估计肌肉力（或扭矩），还要考虑到惯性（抵抗加速度的质量）、粘性（与速度成正比的阻力）、由反对运动的肌肉和肌腱产生的刚度（与位移成正比的弹性力）以及重力。

The dynamic relationship between segments of limbs further complicates sensorimotor transformations. The motion of each segment produces torques, and potentially motions, at all other segments through mechanical interactions. For example, flexion of the upper arm through shoulder rotation can lead to either extension or flexion of the elbow depending on the initial elbow angle. In general, because of the interactions between linked segments, the torques needed to produce a specific change in angle at a particular joint depend not only on the muscles acting directly at this joint but also on the configurations and the motions of all other joints, and especially their acceleration. The brain develops an internal model of these complex mechanical interactions through learning early in childhood. We will see later that this learning is updated throughout life and depends critically on proprioception, which provides the brain with information about changes in muscle length and joint angles.	肢体各节之间的动态关系使感觉运动转换更加复杂。每个节段的运动通过机械相互作用在所有其他节段产生扭力和潜在的运动。例如，通过肩部的旋转，上臂的弯曲可以导致肘部的伸展或弯曲，这取决于初始肘部的角度。一般来说，由于各关节之间的相互作用，在某一关节产生特定角度变化所需的扭矩不仅取决于直接作用于该关节的肌肉，而且还取决于所有其他关节的配置和运动，特别是它们的加速度。大脑在儿童早期通过学习形成了这些复杂的机械互动的内部模型。我们将在后面看到，这种学习在整个生命过程中都在更新，并且关键取决于本体感觉，它为大脑提供了关于肌肉长度和关节角度变化的信息。
Possible starting point	可能的起点
Target line	目标线
Standard deviation of movement endpoint（mm）	运动终点的标准偏差（毫米）
Movement time (ms)	移动时间（毫秒）
Different Coordinate Systems May Be Employed at Different Stages of Sensorimotor Transformations	不同阶段中的感觉运动转换所运用的坐标系统不同

Different coordinate systems are used in sensorimotor transformations and are encoded in several brain regions. Coordinate systems are either extrinsic or intrinsic to the body. Extrinsic coordinate systems relate objects in the outside world to other objects (allocentric coordinates) or to our body **(egocentric coordinates)** using exteroceptive information, usually visual or auditory (Figures 33-5A and B). Intrinsic coordinate systems, such as the set of muscle lengths or set of joint angles (Figure 33-5C), are based on information provided primarily by proprioceptive systems.	在感觉运动转换过程中，会运用不同的坐标系统，并在几个大脑区域进行编码。坐标系统有的是外在的，有的是身体内在的。外在的坐标系统利用外在的感觉信息，通常是视觉或听觉，将外界的物体与其他物体（分配中心坐标）或我们的身体**（自我中心坐标）**联系起来（图 33-5A 和 B）。内在坐标系统，如一组肌肉长度或一组关节角度（图 33-5C），主要基于本体感觉系统提供的信息。
Elucidating the coordinate systems used in sensorimotor transformations is a major endeavor in neuroscience. We will see in later chapters that this issue can be fruitfully studied by examining how the firing patterns of neurons in different parts of the brain encode task features or movement parameters. Such studies aim to determine the variables (such as position or velocity) or type of coordinate system (such as allocentric or egocentric) that the neurons encode.	阐明用于感觉运动转换的坐标系统是神经科学的一项重要工作。我们将在后面的章节中看到，这个问题可以通过研究大脑不同部位的神经元的发射模式如何编码任务特征或运动参数来进行富有成效的研究。这种研究旨在确定神经元编码的变量（如位置或速度）或坐标系统的类型（如分配中心或自我中心）。
Behavioral studies also have used a variety of methods to examine the coordinate systems used in directing movement. One way has been to examine the details of the errors made during movement in different tasks. When subjects are asked to reach a	行为学研究也使用了各种方法来研究指导运动的坐标系统。一种方法是检查不同任务中运动过程中的错误细节。当受试者被要求快速、反复地将手伸向一个目标时，可以用不同的方法测量运动

rapidly and repeatedly to a target, the error in the movements can be measured in different ways. If we average the final location of the hand across many trials, we may find a constant error or bias in the movement. We can examine the distribution of the final locations of the hand about this average position and infer from the patterns of constant and variable error the coordinate system used in the movement (Box 33-2).	中的误差。如果我们在多次试验中将对手的最终位置进行平均计算，我们可能会发现运动中的恒定误差或偏差。我们可以检查手的最终位置在这个平均位置上的分布，并从恒定和可变误差的模式中推断出运动中使用的坐标系统（框 33-2）。
Stereotypical Patterns Are Employed in Many Movements	许多运动均采用传统模式
Given a task, motor plans are under constrained. For example, the hand can move to a target along an infinite number of possible paths, and for each path there is an infinite number of trajectories. Having specified the path and velocity, each point along the path could be reached by any number of combinations of arm joint angles and, owing to the overlapping actions of muscles and the ability to co-contract, each arm configuration could be achieved by many different combinations of muscles.	给定一个任务，运动计划是受限制的。例如，手可以沿着无数条可能的路径向目标移动，而每条路径都有无数条轨迹。在指定了路径和速度后，沿着路径的每一点都可以通过手臂关节角度的任何数量的组合来达到，由于肌肉的重叠动作和共同收缩的能力，每个手臂的配置可以通过许多不同的肌肉组合来实现。
Although we have described different types of sensorimotor transformations, in general, the inverse transformations cannot be uniquely specified. For example, the inverse kinematic transformation that transforms hand positions into joint angles can have many outputs based on the same input. This is because many different combinations of joint angles will put the hand in the same	尽管我们已经描述了不同类型的传感运动学转换，但一般来说，反转换不能被唯一指定。例如，将手的位置转换为关节角度的逆运动学转换可以在相同的输入基础上有许多输出。这是因为许多不同的关节角度组合会使手处于同一位置。运动系统以许多不同

place. The ability of the motor systems to achieve a task in many different ways is called redundancy. If one way of achieving a task is not practical, there is usually an alternative.	的方式实现一项任务的能力被称为冗余性。如果实现一项任务的一种方式不实用，通常会有另一种方式。
Some of the earliest studies of movement examined how the brain determines the duration of a movement. Fitts's law describes the relationship between the amplitude, accuracy, and duration of a movement. This law relates the duration of a movement to the accuracy required of the task, as determined by the target width and amplitude of the movement, and applies to a variety of tasks such as reaching, placing pegs in holes, and picking up objects (Figure 33-8).	一些最早的运动研究考察了大脑如何决定一个运动的持续时间。菲茨定律描述了一个动作的振幅、准确性和持续时间之间的关系。该定律将运动的持续时间与任务所需的准确性联系起来，由运动的目标宽度和振幅决定，适用于各种任务，如伸手、将钉子放入孔中和拿起物体（图 33-8）。
Box 33-2 The Brain's Choice of Spatial Coordinate System Depends on the Task	框 33-2 大脑对空间坐标系的选择取决于任务的需要
When subjects are shown a visual target and asked to reach for it repeatedly, the pattern of errors they make varies with the circumstance of the task. By examining these errors it is possible to assess which coordinate system is used to represent the target position under different conditions.	当受试者看到一个视觉目标并被要求反复地去够它时，他们所犯的错误模式会随着任务的情况而变化。通过检查这些错误，有可能评估在不同条件下用哪种坐标系来表示目标位置。
For example, when subjects are required to move their hands on a horizontal surface and can estimate the starting position of their hands before movement, the pattern of errors indicates planning in "hand-centered" coordinates. The distributions of the endpoints of the movements demonstrate	例如，当受试者被要求在一个水平面上移动他们的手，并能在运动前估算他们手的起始位置时，错误的模式表明在"以手为中心"的坐标中进行规划。运动端点的分布表明，在任务条件下，距离

that, under the conditions of the task, errors in distance and direction are independent of each other (Figure 33-6) and thus that errors in the extent of a movement cannot be predicted from errors in direction. The independence of the two types of errors suggests that for this type of task, subjects estimate distance and direction relative to a specific starting location (that is a movement vector) in Cartesian coordinates.	和方向的错误是相互独立的（图 33-6），因此，运动范围的错误不能从方向的错误中预测出来。这两类错误的独立性表明，对于这种类型的任务，受试者是相对于笛卡尔坐标中的特定起始位置（即运动矢量）来估算距离和方向的。
Conversely, when subjects make large three-dimensional movements to remember visual targets in the dark, a different pattern of error is observed When the target and finger locations at the end of the reach are plotted against each other in terms of spherical coordinates centered on the shoulder, angular errors (elevation and azimuth) are small, whereas errors in the radial extent of the movement are significant (Figure 33-7). Moreover, the two types of errors are not correlated. However, if the target and finger locations are plotted in terms of spherical coordinates centered on the head, the errors are correlated. The fact that the spherical coordinate system centered on the shoulder produces uncorrelated errors suggests that at some stage in the sensorimotor transformation, the target is represented in shoulder-centered coordinates. Recent work suggests that this pattern of errors reflects planning for a final	相反，当受试者在黑暗中做大的三维运动以记住视觉目标时，会观察到不同的错误模式。当以肩部为中心的球面坐标将目标和手指在伸手结束时的位置相互对照时，角度错误（仰角和方位角）很小，而运动的径向范围的错误则很明显（图 33-7）。此外，这两种类型的误差是不相关的。然而，如果目标和手指的位置是以头部为中心的球面坐标来绘制的，那么这些误差是相关的。 以肩部为中心的球面坐标系统产生不相关的错误这一事实表明，在感觉运动转换的某个阶段，目标是以肩部为中心的坐标表示的。最近的工作表明，这种错误模式反映了对最终手部位置的规划，而不是特定的手部运动轨

hand position rather than a particular hand trajectory.	迹。
Despite variations in the movement direction, speed, and location, several aspects of reaching movements are stereotypical or invariant. **First, the hand tends to follow roughly a straight path (Figure 33-9A), although significant curvature is observed for certain movements, particularly vertical movements and movements near the boundaries of the reachable space.** The tendency to make straight-line movements characterizes a large class of movements and is surprising given that the muscles act to rotate joints. Second, a plot of hand speed over time is typically smooth, unimodal, and roughly symmetric (bell-shaped) (Figure 33-9B). This is not the case when movement accuracy requirements are high or corrections to the movement are made.	尽管运动方向、速度和位置有变化，但伸手运动的几个方面是定型的或不变的。**首先，虽然我们能在某些运动，特别是垂直运动和靠近可及空间边界的运动中，观察到明显的弯曲，但是，手的运动轨迹大致呈直线（图 33-9A）。**一大类的运动以直线运动的趋势为特征，考虑到肌肉的作用是旋转关节，这种趋势是令人惊讶的。第二，手的速度随时间变化的曲线通常是平滑的、单模态的和大致对称的（钟形）（图 33-9B）。当运动精度要求很高或对运动进行修正时，情况就不是这样了。
In contrast, the motions of the joints in series (such as the shoulder, elbow, and wrist) are complicated and vary greatly with different initial and final positions. Because rotation at a single joint would produce an arc at the hand, both elbow and shoulder joints must be rotated concurrently to produce a straight path. In some directions the elbow moves more than the shoulder; in others, the reverse occurs. When the hand is moved from one side of the body to the other (see Figure 33-9A, movement from T2 to T5)	相比之下，串联的关节（如肩、肘、腕）的运动就很复杂，而且随着初始和最终位置的不同而变化很大。因为在单个关节的旋转会在手部产生一个弧线，所以肘部和肩部的关节必须同时旋转才能产生一个直线路径。在某些方向上，肘部比肩部移动得更多；而在其他方向上，情况正好相反。当手从身体的一侧移动到另一侧时（见图 33-9A，从 T2 到 T5

one or both joints may have to reverse direction in midcourse. The fact that hand trajectories are more invariant than joint trajectories suggests that the motor system typically controls the hand by adjusting joint rotations and torques to achieve desired hand trajectories.	的运动），一个或两个关节可能要在中途扭转方向。手的运动轨迹比关节的运动轨迹更不稳定，这表明运动系统通常通过调整关节的旋转和扭矩来控制手，以达到理想的运动轨迹。
Invariances can also be seen in more complex movements. The nervous system puts together complex actions from elemental movements that have highly stereotyped spatial and temporal characteristics. For example, the seemingly continuous motion of drawing a figure eight actually consists of several discrete movements that are roughly constant in duration, regardless of their size. Moreover, there is a relationship between the curvature of each elemental movement and speed: Subjects tend to slow the hand as the curvature of the path increases. Empirical studies have shown that for many tasks a power law relation, the two-thirds power law, governs the relationship between hand speed and path curvature (Figure 33-10).	在更复杂的运动中也可以看到不变性。神经系统将具有高度定型的空间和时间特征的基本动作组合成复杂的动作。例如，看似连续的画八字的动作实际上是由几个离散的动作组成的，无论其大小，其持续时间都是大致不变的。此外，每个元素运动的曲率和速度之间存在着一种关系：随着路径曲率的增加，受试者倾向于减缓手的速度。经验研究表明，对于许多任务来说，幂律关系，即三分之二幂律，支配着手速和路径曲率之间的关系（图 33-10）。
The simple spatiotemporal elements of a complex movement are called movement primitives or movement schemas. Like the simple lines, ovals, or squares in computer graphics programs, movement schemas can be scaled in size or time. The neural representations of complex actions, such as prehension, writing, typing, or drawing, are	复杂运动的简单时空元素被称为运动基元或运动模式。就像计算机图形程序中的简单线条、椭圆或方块一样，运动模式可以按大小或时间进行调整。复杂动作的神经表征，如预感、书写、打字或绘图，被认为是这些简单时空

thought to be stored sets of these simple spatiotemporal elements.	元素的存储集合。
Recent computational studies of a variety of tasks suggest that **a repertory of movement schemas is the result of a process in which all possible ways of moving are ranked and the best is selected.** This idea implies that either through evolution or motor learning our movements improve progressively until some limit is reached. To quantify how good or bad a movement the brain assigns a cost to each possible movement, and the movement with the lowest cost is executed. The cost is specified as some function of the movement and task, and the challenge to researchers has been to determine, from observed movement patterns and perturbation studies, the form of this function.	最近对各种任务的计算研究表明，**运动模式汇编是一个过程的结果，在这个过程中，大脑会排列出所有可能的运动方式，并从中选择出最好的**。这个想法意味着，无论是通过进化还是运动学习，我们的运动都在逐步改善，直到达到某种极限。 为了量化一个动作的好坏，大脑给每个可能的动作分配了一个成本，然后执行成本最低的动作。成本被指定为运动和任务的某些函数，研究人员面临的挑战是如何从观察到的运动模式和扰动研究中确定这个函数的形式。
The cost may be kinematic; for example, lack of smoothness in a movement can be corrected by minimizing the rate of change of hand acceleration summed over a movement. Alternatively, the cost may be dynamic. For example, because the variability in the motor output is proportional to the magnitude of the motor command, repetition of the same sequence of intended motor commands many times will lead to a distribution of actual movements. Modifying the sequence of motor commands can control aspects of this	成本计算可以具有运动学性质；例如，运动中缺乏平稳性可以通过最小化运动中手的加速度总和的变化率来纠正。另外，成本计算可能是动态的。例如，由于马达输出的变异性与马达指令的大小成正比，多次重复同一序列的预定马达指令将导致实际运动的分布。修改运动指令的顺序可以控制这种分布的各个方面，如运动结束时手的位置分布。在一个简单的瞄准运动中，成本是最终

distribution, such as the spread of positions of the hand at the end of the movement. In a simple aiming movement, the cost is the final error, as measured by the variability about the target. A model that minimizes this cost would accurately predict the trajectories of both eye and arm movements.	的误差，由关于目标的变化率来衡量。一个使这个成本最小化的模型将准确地预测眼睛和手臂的运动轨迹。
Motor Signals Are Subject to Feedforward and Feedback Control	运动信号受制于前馈和反馈控制
So far, we have focused on how sensory inputs are used to plan a movement and why the resulting movements can have errors. Sensory inputs to the motor systems during a movement provide information about errors that arise from neural noise, from inaccuracies in the motor commands as a result of flaws in the internal models, or from changes in the outside world, such as the unexpected motion of a target. We now examine what part these errors play in two forms of motor control, feedforward and feedback control.	到目前为止，我们主要关注的是感觉输入是如何被用来计划运动的，以及为什么所产生的运动会有误差。在运动过程中对运动系统的感觉输入提供了错误的信息，这些错误源于神经噪音以及内部模型的缺陷，从而导致的运动指令不准确或外部世界的变化，如目标的意外运动。我们现在研究这些错误在两种形式的运动控制(前馈和反馈控制)中起什么作用。
Feedforward Control Does Not Use Sensory Feedback	前馈控制不使用感觉反馈
Movements that are not correctible during the movement are often termed ballistic. This term is ordinarily applied to the trajectory of unpowered projectiles (such as ballistic missiles) that, once launched, can no longer be controlled and are subject only to gravity. Because arm movements can potentially be controlled throughout their course, however, the term feedforward	在运动过程中无法纠正的运动通常被称为弹道。这个术语通常适用于无动力弹丸（如弹道导弹）的弹道，一旦发射，就不能再控制，只能受重力影响。然而，由于手臂运动有可能在其整个过程中受到控制，前馈控制一词更准确地描述了弹道。

control more accurately describes the trajectory.	
Feedforward commands are generated without regard to the consequences. Such commands are also termed open-loop because the sensorimotor loop is not completed by sensory feedback (Figure 33-11A).	前馈指令是在不考虑后果的情况下产生的。这种指令也被称为开环，因为感觉运动环路并不由感觉反馈完成（图 33-11A）。
Open-loop control is advantageous if we consider the delays inherent in the sensorimotor system. Both conversion of stimulus energy into neural signals by stimulus receptors and the conveyance of the sensory signals to central neurons take time. For example, visual feedback can take approximately 100 ms to be processed in the retina and transmitted to the visual cortex. In addition to delays in the peripheral sensory system, there are also delays in central processing, in the transmission of efferent signals to motor neurons, and in the response of muscles. In all, the combined sensorimotor loop delay is appreciable, approximately 200 ms for a response to a visual stimulus. This delay means that rapid movements, such as the saccades of the eye that last less than 100 ms, cannot use sensory feedback to guide the eye onto a target.	如果我们考虑到感觉运动系统中固有的延迟，开环控制是有利的。刺激受体将刺激能量转化为神经信号和将感觉信号传递给中枢神经元都需要时间。例如，视觉反馈在视网膜上的处理和传送到视觉皮层大约需要 100 毫秒。除了外周感觉系统的延迟外，在中枢处理、向运动神经元传输感知信号和肌肉反应方面也有延迟。总的来说，综合感觉-运动环路的延迟是明显的，对视觉刺激的反应大约为 200 毫秒。这种延迟意味着快速运动，如持续时间少于 100 毫秒的眼球收缩，不能使用感觉反馈来引导眼球到达目标 。
Even with slower movements, such as deliberate reaching, which can take approximately 500 ms, sensory information	即使是较慢的运动，如故意伸手，可能需要大约 500 毫秒，感觉信息也不能用来指导运动的初

cannot be used to guide the initial part of a movement, so open-loop control must be used. This open-loop component can be clearly demonstrated. Both the initial speed and the acceleration of the hand during reaching are proportional to the distance of the target. **This and the straightness of hand paths mean that the extent of a movement is planned before the movement is initiated, and the movement is generated in a feedforward manner (Figure 33-12).**	始部分，所以必须使用开环控制。这种开环控制有理可依。在伸手过程中，手的初始速度和加速度都与目标的距离成正比。**这一点和手部路径的直线性意味着，运动范围在运动开始之前就已经规划好了，并通过前馈方式产生的（图 33-12）。**
Open-loop control also has disadvantages. Any movement errors caused by inaccuracies in planning feedback adjustment would be seen or execution will not be corrected, and therefore will compound themselves over time or successive movements. The more complex the system under control, the more difficult it is to arrive at a perfect inverse model through learning. For example, the **vestibulo-ocular reflex** (see Chapter 40) uses open-loop control to maintain fixation during head rotation. This is a very efficient system as the dynamics of the eye are relatively simple, and the rotation of the head can be directly sensed by the vestibular labyrinth. The complexity of the arm, however, makes it very difficult to optimize an inverse model, and thus the control of hand movement requires some form of error correction.	开环控制也有弊端。任何由规划反馈调整不准确引起的运动误差都很明显，反而会随着时间的推移或连续运动而加剧。控制系统越复杂，就越难通过学习获得完美的逆模型。例如，**前庭-眼动反射**（见第 40 章）使用开环控制来保持头部旋转时的定点。这是一个非常高效的系统，因为眼球的动态相对简单，前庭迷宫可以直接感知头部的转动。然而，手臂的复杂性使得逆模型的优化非常困难，因此手部运动的控制需要某种形式的误差修正。

Feedback Control Uses Sensory Signals to Correct Movements	反馈控制利用感觉信号纠正动作
The simplest form of feedback control is one in which the control system generates a fixed response. System is seen in most central heating systems in which a thermostat is set to a desired temperature. When the house temperature falls below the specified level, the heating is turned on until the temperature reaches that level. Although such a system is simple and can be effective, it has the drawback that the amount of heat being put into the house does not relate to the discrepancy between the actual and desired temperature (the error). A better system is one in which the control signal is proportional to the error.	最简单的反馈控制形式是控制系统产生一个固定的响应。在大多数中央供暖系统中，恒温器被设定为所需温度。当室内温度低于指定水平时，暖气就会开启，直到温度达到该水平。虽然这种系统简单有效，但它的缺点是，向室内输入的热量与实际温度和期望温度之间的差异（误差）无关。更为完善的系统是控制信号与误差成正比的系统。
Such proportional control of movement involves sensing the error between the actual and desired position of, for example, the hand. The size of the corrective motor command is in proportion to the size of the error and in a direction to reduce the error. The amount by which the corrective motor command is increased or decreased per unit of positional error is called the gain (Figure 33-13). By continuously correcting a movement, feedback control can be robust both to noise in the sensorimotor system and to environmental perturbations.	这种运动比例控制包括感知实际位置和期望位置之间的误差，例如手的位置。纠正电机指令的大小与误差大小成正比，其方向是减小误差。每单位位置误差所增加或减少的纠正电机指令量称为增益（图 33-13）。通过持续纠正运动，反馈控制可以抵御传感运动系统中的噪声和环境干扰.
In most motor systems movement control is achieved through both feedforward and feedback processes. Because sensory	在大多数运动系统中，运动控制都是通过前馈和反馈两个过程实现的。由于在运动的最初阶段无

feedback is not available for the first portion of a movement, feedforward processes generate the initial motor command only. As the movement progresses, information on performance becomes available, allowing feedback control to play a role.	法获得感觉反馈，前馈过程只能产生最初的运动指令。随着运动的进行，有关运动表现的信息有其可用之处，反馈控制就能发挥作用"。
When lifting an object between thumb and index finger, for example, sufficient grip force (perpendicular force between the digits and the object's surface) must be generated to prevent slippage owing to load force (tangential force between the digit and object surface arising from the object's weight). We use feedforward control to set our grip force and the lifting force in accordance with the expected slipperiness and weight of the object. If cutaneous receptors indicate that slippage is occurring, our grip force is increased immediately through rapid feedback control (Figure 33-14). Because cutaneous information on slippage evokes a motor command to increase grip force only when the object is being lifted, this feedback circuit is said to be "gated" during lifting.	"例如，当用拇指和食指抬起一个物体时，必须产生足够的抓力（指头与物体表面之间的垂直力），以防止因负载力（物体重量在指头与物体表面之间产生的切向力）而打滑。我们使用前馈控制，根据预期的滑动性和物体重量来设定抓取力和提升力。如果皮肤感受器显示正在发生滑动，我们就会通过快速反馈控制立即增加握力（图 33-14）。由于只有当物体被提起时，有关打滑的皮肤信息才会唤起增加握力的运动指令，因此这一反馈回路在提起过程中被称为"门控"。
Feedback control cannot generate a command in anticipation of an error: It is always driven by an error. Feedforward control, conversely, is based only on a desired state and can therefore null the error.	反馈控制无法在预期出现错误时产生指令：它总是由误差驱动。反之，前馈控制仅基于预期状态，因此可以使误差无效"。
Prediction Compensates for Sensorimotor Delays	预测可以弥补感觉运动的延迟行动
Accurate feedback control of movement	"准确的运动反馈控制需要有关身

requires information on the body's current state, for example, the positions and velocities of our body segments. However, sensory feedback from the periphery is both noisy and slow. Delays in feedback can lead to problems during a movement, as the delayed information does not reflect the present state of the body and world. Two strategies can compensate for such delays and thus increase the accuracy of sensory feedback during movement: intermittency of movement and prediction of changes in body states due to movement. With intermittency, movement is momentarily interrupted by rest, as in eye sac-cades and manual tracking. Provided the interval of rest is greater than the time delay of the sensorimotor loop, intermittency fosters more accurate sensory feedback.	体当前状态的信息，例如我们身体各部分的位置和速度。然而，来自外围的感觉反馈既嘈杂又缓慢。反馈延迟会导致运动过程中出现问题，因为延迟的信息无法反映身体和世界的当前状态。有两种策略可以弥补这种延迟，从而提高运动过程中感觉反馈的准确性：运动的间歇性和对运动引起的身体状态变化的预测。在间歇运动中，运动会因休息而瞬间中断，如眼球移动和手动追踪。只要休息的时间间隔大于感觉运动环路的时间延迟，间歇就能促进更准确的感觉反馈。
Prediction is a better strategy and can form a major component of a state estimator. Although sensory signals provide necessary information about the body, the motor command also provides useful information. If both the current state of the body and the descending motor command are known, the next state of the body can be estimated. This estimate is derived from a forward model that predicts how the body will change in response to the motor command. Because this estimate is predictive, it is time-advanced, thereby compensating for the feedback delays. However, this estimate will	预测是一种更好的策略，可以成为状态估计器的主要组成部分。虽然感觉信号提供了有关身体的必要信息，但运动指令也提供了有用的信息。如果已知身体的当前状态和下降的运动指令，就可以对身体的下一个状态进行估计。这个估计值来自一个前向模型，该模型预测了身体将如何响应电机指令而发生变化。由于该估计是预测性的，因此具有时间提前性，从而弥补了反馈延迟。

tend to drift over time if the forward model is not perfectly accurate.	不过，如果前向模型不完全准确，这种估计值就会随着时间的推移而偏移。
The drawbacks of using only sensory feedback or only motor prediction can be ameliorated by monitoring both and using a forward model to estimate the current state of the body. A neural apparatus that does this is known as an observer model. The major objectives of the observer model are to compensate for sensorimotor delays and to reduce uncertainty in the estimate of the state of the body owing to noise in both the sensory and motor signals (Figure 33-15). Such a model has been supported by empirical studies of how the nervous system estimates hand position, posture, and head orientation. The nervous system has several different internal models of control that use prediction and sensory feedback to different extents. The comparative advantages of these various models are nicely illustrated by differences in object manipulation under different conditions. When the object's behavior is unpredictable, sensory feedback provides the most useful signal for estimating load. For example, when flying a kite, we need to adjust our grip almost continuously in response to unpredictable motions of the kite. When dealing with such unpredictability, grip force needs to be high to prevent slippage because it tends to lag behind load force (Figure 33-16A).	通过监测这两种反馈并使用前向模型来估计身体的当前状态，可以改善仅使用感觉反馈或仅使用运动预测的缺点。观察者模型的主要目的是补偿感觉运动延迟，并减少由于感觉和运动信号中的噪声而导致的身体状态估计的不确定性（图 33-15）。对神经系统如何估计手的位置、姿势和头部方向的实证研究支持这种模型。神经系统有几种不同的内部控制模型，它们在不同程度上使用预测和感觉反馈。在不同条件下操作物体的差异很好地说明了这些不同模型的比较优势。当物体的行为不可预测时，感觉反馈为估计负荷提供了最有用的信号。例如，在放风筝时，我们需要根据风筝不可预测的运动不断调整握力。在应对这种不可预测性时，握力需要很高以防止滑动，因为它往往落后于负荷力（图 33-16A）。

However, when handling objects with stable properties, predictive control mechanisms can be effective. For example, when the load is increased by a self-generated action, such as moving the arm, the grip force increases instantaneously with load force (Figure 33-16B). Sensory detection of the load would be too slow to account for this rapid increase in grip force. Such predictive control is essential for the rapid movements commonly observed in dexterous behavior.	不过，在处理具有稳定特性的物体时，预测控制机制会很有效。例如，当负载因手臂移动等自发动作而增加时，抓取力会随着负载力的增加而瞬时增加（图 33-16B）。对负载的感官检测速度太慢，无法解释握力的这种快速增加。这种预测控制对于灵巧行为中常见的快速运动至关重要。
The discrepancy between actual and predicted sensory feedback is also essential in motor control. For example, when we pick up an object, we anticipate when the object will lift off. The brain is particularly sensitive to the occurrence of unexpected events or the nonoccurrence of an expected event. Thus, if an object is lighter or heavier than expected, and therefore is lifted too early or cannot be lifted, reactive responses are evoked. The brain seems to pay particular attention to these critical moments to determine whether the subsequent actions that are part of the task should proceed.	实际感觉反馈与预测感觉反馈之间的差异在运动控制中也至关重要。例如，当我们拿起一个物体时，我们会预测物体何时会腾空。大脑对意外事件的发生或预期事件的不发生特别敏感。因此，如果一个物体比预期的要轻或重，从而过早地提起或无法提起，就会引起反应性反应。大脑似乎特别关注这些关键时刻，以决定是否应继续执行任务中的后续行动。
In addition to its use in compensating for sensory feedback delays, prediction is a key element in perceptual processing. Sensory feedback can originate from two sources: either external sources or our own movement. In the sensory receptor these two sources are not distinguished, however, and sensory signals do not carry a label "external	除了用于补偿感觉反馈延迟之外，预测也是知觉处理过程中的一个关键因素。感觉反馈有两个来源：外部来源或我们自身的运动。然而，在感觉感受器中，这两种来源并没有区分，感觉信号也没有"外部刺激"或"内部刺激"的

stimulus" or "internal stimulus."	标签。
Sensitivity to external events can be amplified by reducing the feedback from our own movement. Thus, predictions of sensory signals that arise from our own movements are subtracted from the total sensory feedback, thereby enhancing the signals that cany information about external events. Such a predictive mechanism is responsible for the fact that tickling oneself is a less intense experience than tickling by another. When participants are asked to tickle themselves with a time delay introduced between the motor command and the resulting tickle, the greater the time delay the more ticklish the sensation. As the time delay increases, the predictor becomes more inaccurate, thereby failing to cancel the sensory feedback resulting in the tickle sensation.	对外界事件的敏感度可以通过减少来自我们自身运动的反馈来放大。因此，从总的感觉反馈中减去由我们自身运动产生的感觉信号的预测，从而增强了能够提供外部事件信息的信号。这种预测机制是造成自己挠痒的强烈程度低于他人挠痒的原因。当参与者被要求给自己挠痒时，在动作指令和挠痒的结果之间引入时间延迟，时间延迟越长，挠痒的感觉就越强烈。随着时间延迟的增加，预测器会变得更加不准确，从而无法消除导致搔痒感的感觉反馈"。
Sensory Processing Is Different for Action and Perception	在动作和感知方面，感觉的处理有所不同
A growing body of research supports the idea that the sensory information used to control actions is processed in neural pathways that are distinct from the afferent pathways that contribute to perception. Mel Goodale and David Milner have proposed that visual information flows in two streams in the brain (see Chapter 25). A dorsal stream projects to the posterior parietal cortex and is particularly involved in the use of vision for action (see Chapter 38).	"越来越多的研究支持这样一种观点，即用于控制行动的感觉信息是在神经通路中进行处理的，而这些神经通路与有助于感知的传入通路不同。梅尔·古代尔和戴维·米尔纳提出，视觉信息在大脑中有两条流（见第 25 章）。背侧信息流投射到后顶叶皮层，特别参与视觉在行动中的应用（见第

Conversely, a ventral stream projects to the inferotemporal cortex and is involved in conscious visual perception (see Chapter 28).	38 章）。相反，腹侧流投射到颞下皮层，参与有意识的视觉感知（见第 28 章）。
This distinction between the uses of vision for action and perception is based on a double-dissociation seen in patient studies. For example, the patient D. F. developed visual agnosia after damage to her ventral stream. She is unable, for example, to explain the orientation of a slot either verbally or with her hand. However, when asked to perform a simple action, such as putting a card through the slot, she has no difficulty orienting her hand appropriately to put the card through the slot. Conversely, patients with damage to the dorsal stream can develop optic ataxia in which perception is intact, but control is affected.	视觉用于行动和感知之间的这种区别是基于患者研究中出现的双重分离现象。例如，患者 D. F.在腹侧流受损后出现了视觉失认症。例如，她无法用语言或手解释槽的方向。然而，当要求她做一个简单的动作时，比如把一张卡片放进插槽里，她却能正确地调整手的方向，把卡片放进插槽里。相反，背侧流受损的患者会出现视共济失调，在这种情况下，感知能力完好无损，但控制能力受到影响。
Although the distinction between perception and action arose from clinical observations, it can also be seen in normal people, as in the size—weight illusion. When lifting two objects of different size but equal weight, people report that the smaller object feels heavier. This illusion, first documented more than 100 years ago, is both powerful and robust. It does not lessen when a person is informed that the objects are of equal weight and does not weaken with repeated lifting.	虽然感知和行动之间的区别是通过临床观察得出的，但在正常人身上也能看到这种区别，比如大小-重量错觉。当举起两个大小不同但重量相等的物体时，人们会感觉较小的物体更重。这种错觉在 100 多年前首次被记录下来，它既强大又稳固。当一个人被告知两个物体重量相等时，这种错觉并不会减轻，也不会随着反复提举而减弱。
When subjects begin to lift large and small objects that weigh the same, they generate	当受试者开始举起重量相同的大

larger grip and load forces for the larger object because they assume that larger objects are heavier. After alternating between the two objects, they rapidly learn to scale their fingertip forces precisely for the true object weight (Figure 33-17). This shows that the sensorimotor system recognizes that the two weights are equal. Nevertheless, the size-weight illusion persists, suggesting not only that the illusion is a result of high-level cognitive centers in the brain but also that the sensorimotor system can operate independently of these centers.	小物体时，他们会对较大的物体产生较大的握力和负荷力，因为他们认为较大的物体更重。在交替使用两种物体后，他们很快就能学会根据物体的真实重量精确地调整指尖力（图 33-17）。这表明，感觉运动系统能识别出两个重量相等的物体。尽管如此，大小-重量错觉仍然存在，这不仅表明这种错觉是大脑高级认知中枢的结果，而且也表明感觉运动系统可以独立于这些中枢运行"。
Motor Systems Must Adapt to Development and Experience	运动系统必须要适应于发育和经验
Animals have a remarkable capacity for learning new motor skills through their interaction with the environment. This learning is distinct from and independent of the development of skills through maturation. Although evolution can hard-wire some motor behaviors, such as the ability of a foal to stand, motor behavior in general must adapt to new and varying environments.	动物通过与环境的互动学习新的运动技能的能力非同一般。这种学习有别于技能的成熟发展，也独立于技能的成熟发展。虽然进化可以使某些运动行为（如小马驹的站立能力）硬线化，但一般的运动行为必须适应新的和变化的环境。
New motor skills cannot be acquired by a fixed neural control system. Sensorimotor control systems must constantly adapt over a lifetime as body size and proportions change, thereby maintaining an appropriate relationship between motor commands and body mechanics. In addition, learning is the	新的运动技能无法通过固定的神经控制系统获得。感知运动控制系统必须在一生中随着身体大小和比例的变化而不断调整，从而保持运动指令与身体力学之间的适当关系。此外，学习是获得由

only way to acquire motor skills that are defined by social convention, such as writing or dancing.	社会习俗定义的运动技能（如写作或舞蹈）的唯一途径。
Most forms of motor learning involve procedural or implicit learning, so-called because subjects are generally unable to express what it is they have learned. Implicit learning often takes place without consciously thinking about it and can be retained for extended periods of time without practice (see Chapter 66). Typical examples of procedural learning are learning to ride a bicycle or play the piano. In contrast, explicit or declarative learning involves the acquisition of knowledge that can be expressed in statements about the world and is available to introspection (see Chapter 67). Memorizing the names and routes of the cranial nerves or directions to the local hospital are examples of explicit learning. Declarative memory tends to be easily forgotten, although repeated exposure can lead to long-lasting retention.	大多数形式的运动学习涉及程序性学习或隐性学习，之所以称之为隐性学习，是因为受试者通常无法表达他们学到了什么。内隐学习通常是在不自觉的情况下进行的，无需练习就能保持较长时间（见第 66 章）。程序性学习的典型例子是学习骑自行车或弹钢琴。与此相反，显性或陈述性学习涉及的知识可以用关于世界的陈述来表达，并且可以进行内省（见第 67 章）。记住颅神经的名称和路线或当地医院的路线就是显性学习的例子。陈述性记忆往往很容易遗忘，不过反复接触可以使记忆长期保持。
Motor learning can occur more or less immediately or require some time. One learns to pick up an object of unknown weight almost immediately and learns to ride a bicycle after a little practice, but mastering the piano requires years. These different timescales may reflect the intrinsic difficulty of the task as well as evolutionary constraints that have to be unlearned to perform the task. For example, piano	运动学习可以或多或少立即发生，也可能需要一些时间。一个人几乎马上就能学会拿起重量未知的物体，稍加练习就能学会骑自行车，但掌握钢琴则需要数年时间。这些不同的时间尺度可能反映了任务的内在难度，也反映了执行任务时必须摆脱的进化限制。例如，弹钢琴需要学习对手

playing requires learning precise control of the fingers, whereas in normal movements, such as reaching and grasping, individuated finger movements are rare.	指的精确控制，而在伸手和抓握等正常动作中，单独的手指动作很少见。
Motor Learning Involves Adapting Internal Models for Novel Kinematic and Dynamic Conditions	涉及新型运动学和动力学条件调整内部模型的运动学习
Sensorimotor transformations have kinematic and dynamic components. Kinematic transformations relate events in different spatial coordinate systems, such as joint angles of the arm and the position of the hand in space. To control a computer mouse, for example, we must learn the kinematic transformation between the handheld mouse and the image of the cursor on the screen. Dynamic transformations relate forces acting at the joints to the motion of the system. We must relate the forces we apply to the mouse to the resulting movement, a transformation that depends on the inertia of the mouse and the friction between the mouse and pad. The kinematics and dynamics of movement vary greatly as we grow and interact with new objects. The brain adapts by reorganizing or adjusting motor commands to generate new actions.	"感觉运动转换"包含运动学和动力学两个部分。运动变换将不同空间坐标系中的事件联系起来，例如手臂的关节角度和手在空间中的位置。例如，要控制电脑鼠标，我们必须学习手持鼠标与屏幕上光标图像之间的运动变换。动态变换将作用在关节上的力与系统的运动联系起来。我们必须将作用在鼠标上的力与运动结果联系起来，这种变换取决于鼠标的惯性以及鼠标和鼠标垫之间的摩擦力。随着我们的成长和与新物体的互动，运动的运动学和动力学会发生很大变化。大脑会通过重组或调整运动指令来产生新的动作。
As we saw earlier, we normally move the hand in a straight line to reach an object. Unexpected dynamic interactions may produce curved paths, but subjects learn to anticipate these effects. This learning is conveniently studied by having subjects	正如我们在前面所看到的，我们通常是沿着一条直线移动手去够一个物体。意料之外的动态互动可能会产生弯曲的路径，但受试者可以通过学习来预测这些影

make pointing movements with an apparatus through which novel forces can be applied to the arm (Figure 33-18A). For example, applying a force that is proportional to the speed of the hand but which acts at right angles to the direction of movement forces the hand into a brief curving movement before reaching the target. Over time the subject adapts to this perturbation and is able to maintain a straight-line movement (Figure 33-18D).	响。研究这种学习的方法很简单，就是让受试者用一个可以向手臂施加新力的装置来做指向运动（图 33-18A）。例如，施加一个与手的速度成正比但与运动方向成直角的力，迫使手在到达目标之前做短暂的弯曲运动。随着时间的推移，受试者会适应这种干扰，并能够保持直线运动（图 33-18D）。
Subjects might adapt to such a situation in two possible ways. First, they could co-contract the muscles in their arm, thereby stiffening the arm and reducing the impact of the perturbation. Alternatively, they could learn an internal model that compensates for the expected forces, one that uses a new set of motor commands. By examining the subjects, movements after the force is turned off, we can distinguish between these two forms of learning. If the arm simply stiffens, it should continue to move in a straight path. If a new internal model is learned, the new model should compensate for a force that no longer exists, thereby producing a path in the direction opposite from the earlier perturbation. In fact, when the force is turned off, subjects show a large after-effect in the opposite direction, demonstrating that they had learned to compensate for the perturbation (Figure 33-18D).	受试者可以通过两种可能的方式适应这种情况。首先，他们可以共同收缩手臂上的肌肉，从而使手臂变硬，减少扰动的影响。或者，他们可以学习一种内部模型来补偿预期的力，即使用一套新的运动指令。通过检查受试者在力被关闭后的动作，我们可以区分这两种学习形式。如果手臂只是变得僵硬，那么它应该继续沿着直线运动。如果学习了一个新的内部模型，那么新模型就应该对不再存在的力进行补偿，从而产生一条与先前扰动方向相反的路径。事实上，当力被关闭时，受试者会在相反方向上表现出很大的后效应，这表明他们已经学会了对扰动进行补偿（图 33-18D）。

Although motor learning often takes much practice, once a task is no longer performed de-adaptation is typically quite swift. The context of the movement, that is the sensory inputs associated with a particular task, can be enough to switch behavior. When subjects wear prismatic glasses that rotate visual space, for example, they initially mis reach targets but soon learn to reach correctly. After repeated trials the contextual cue of the feel of the glasses, without the prisms in place, is sufficient to switch subjects into behavior suitable with the prisms.	虽然运动学习往往需要大量练习，但一旦不再执行任务，去适应通常会非常迅速。运动的背景，即与特定任务相关的感觉输入，足以改变行为。例如，当受试者戴上能旋转视觉空间的棱镜眼镜时，他们最初会误触目标，但很快就能学会正确触及目标。经过反复试验后，在不佩戴棱镜的情况下，眼镜触感的情境提示足以让受试者转换为适合佩戴棱镜的行为"。
Kinematic and Dynamic Motor Learning Rely on Different Sensory Modalities	运动学和动力学运动学习依赖于不同的感觉模式
Not all sensory modalities are equally important in learning motor tasks. In learning dynamic tasks, proprioception is more important than vision. We normally learn dynamic tasks equally well with or without vision. Patients who have lost proprioception have particular difficulty controlling the dynamic properties of their limbs (Box 33-3) or learning new dynamic tasks without vision.	"在学习运动任务时，并非所有的感官模式都同等重要。在学习动态任务时，本体感觉比视觉更重要。通常情况下，无论有没有视觉，我们学习动态任务的效果都一样好。失去本体感觉的患者在控制肢体的动态特性（框 33-3）或在没有视觉的情况下学习新的动态任务时会遇到特定的困难。
However, the same patients are easily able to adapt to drastic kinematic changes, such as tracing a drawing while viewing their hand in a mirror. In fact, these subjects perform better than normal subjects at such a task, perhaps because they have learned to guide their movements visually and, because of the	然而，同样的病人却很容易适应剧烈的运动变化，例如在镜子中观察自己的手时描画图画。事实上，这些受试者在此类任务中的表现比正常受试者更好，这可能是因为他们已经学会了用视觉来

lack of proprioception, do not experience any conflict between vision and proprioception.	指导自己的动作，而且由于缺乏本体感觉，他们不会在视觉和本体感觉之间产生任何冲突"。
Box 33-3 Proprioception Is Critical for Planning Hand Trajectories and Controlling Dynamics	框 33-3 本体感觉对于规划手部轨迹和控制动态至关重要
Sensory neuropathies selectively damage the large-diameter sensory fibers in peripheral nerves and dorsal roots that carry most proprioceptive information. Impairments in motor control resulting from loss of proprioception have fascinated neurologists and physiologists for well over a century. Studies of patients with sensory neuropathies provide invaluable insight into the interactions between sensation and movement planning.	"感觉神经病会有选择性地损伤周围神经和脊髓根中的大直径感觉纤维，而这些纤维携带着大部分本体感觉信息。一个多世纪以来，神经学家和生理学家一直对本体感觉缺失导致的运动控制障碍着迷不已。通过对感觉神经病患者的研究，我们可以深入了解感觉与运动规划之间的相互作用。
As expected, such patients lose joint position sense and vibration and fine tactile sensations (as well as tendon reflexes), but the sense of pain and temperature are fully preserved. These patients are unable to maintain a steady posture, for example while holding a cup or standing, with the eyes closed. Movements also become clumsy, uncoordinated, and inaccurate.	不出所料，这类患者会失去关节位置感、振动和细微触觉（以及肌腱反射），但痛觉和温度觉却完全保留。这些患者无法保持稳定的姿势，例如在拿杯子或站立时，无法闭上眼睛。动作也变得笨拙、不协调和不准确。
Some recovery of function may occur over many months as the patient learns to use vision as a substitute for proprioception, but this compensation leaves patients completely incapacitated in the dark. Some of this difficulty reflects an inability to	随着患者学会用视觉来替代本体感觉，其功能可能会在数月内得到一定程度的恢复，但这种代偿使患者在黑暗中完全丧失能力。这种困难在一定程度上反映了患者无法察觉在看不见的动作中出

detect errors that develop during unseen movements, as occurs if the weight of an object or resistance differs from expectation.	现的错误，例如当物体的重量或阻力与预期不同时就会出现这种错误。
However, this is not all. When the limb cannot be seen, errors in feedforward control of movements increase over a few minutes and patients become uncertain of where their hands actually move. This is seen clearly in the succession of movements in Figure 33-19A. Movements that are straight and accurate with vision become increasingly curved; instead of stopping, movements drift off to one side or another without the subject's awareness. Thus, proprioception is needed to update both inverse models used to control movement and forward models used to estimate body positions resulting from motor commands.	然而，这还不是全部。当看不到肢体时，运动前馈控制的错误会在几分钟内增加，患者会不确定自己的手究竟在哪里移动。从图 33-19A 中的连续动作可以清楚地看出这一点。视觉上笔直而准确的动作变得越来越弯曲；动作非但没有停止，反而在受试者毫无察觉的情况下偏向一侧或另一侧。因此，需要本体感觉来更新用于控制运动的逆向模型和用于估计运动指令产生的身体位置的正向模型。
The defects in these models are revealed by examining the errors that occur when the hand moves to targets in different directions (Figure 33-19B). In moving to equidistant targets in many directions, a normal subject moves his hand approximately the same distance in all directions. For patients with proprioceptive loss, the distance moved varies with the direction of movement; movements along the 45-degree axis, perpendicular to the forearm, overshoot the target.	通过观察手向不同方向的目标移动时出现的误差，可以发现这些模型的缺陷（图 33-19B）。在向多个方向的等距目标移动时，正常人的手在所有方向上移动的距离大致相同。对于本体感觉缺失的患者来说，移动的距离随移动方向而变化；沿着垂直于前臂的 45 度轴线移动时，会偏离目标。
These variations match changes in the inertial resistance of the arm. When the hand moves in the direction of the	**这些变化与手臂惯性阻力的变化相匹配。当手沿前臂方向同时移**

forearm (moving both arm and forearm), inertia is two to three times greater than when the hand moves perpendicular to the forearm (moving the forearm alone). Changes in inertia with movement direction fit an elliptical contour. This means that a constant force applied perpendicularly would accelerate the forearm two to three times faster than one applied in the same direction as the forearm.	**动手臂和前臂时，惯性比手垂直于前臂移动时大 2 到 3 倍。**惯性随运动方向的变化符合椭圆轮廓。这意味着，垂直施加一个恒定的力，前臂的加速度要比与前臂同方向施加的力快两到三倍。
In all subjects acceleration does indeed vary with movement in different directions, but normal subjects plan movements of shorter duration in directions with lower inertia. In contrast, patients without proprioception are unable to vary the duration (unless they see their limb before moving). Errors therefore reflect the rapid decay of the patient's internal model of limb inertia.	在所有受试者中，加速度确实会随着不同方向的运动而变化，但正常受试者在惯性较小的方向上计划运动的持续时间较短。相反，没有本体感觉的患者则无法改变持续时间（除非他们在移动前看到自己的肢体）。因此，错误反映了患者肢体惯性内部模型的快速衰减。
Another form of error occurs in movements with rapid direction reversals. Analyses of the joint torques during these movements show that subjects with intact sensation anticipate intersegmental torques, whereas those without proprioception fail to do so (Figure 33-20).	另一种形式的误差出现在方向快速逆转的动作中。对这些运动过程中关节扭矩的分析表明，感觉完整的受试者能够预测节间扭矩，而没有本体感觉的受试者则不能预测（图 33-20）"。
Figure 33-20 Patients lacking proprioception cannot make an accurate movement that requires a rapid reversal in path. In normal subjects the joint angles for the elbow and shoulder show good alignment, leading to an accurate reversal. In subjects who lack	图 33-20 缺乏本体感觉的患者无法做出需要快速扭转路径的准确动作。在正常人身上，肘部和肩部的关节角度显示出良好的对齐，从而导致准确的反转。在缺

proprioceptive input the timing of the joint reversal is poor, leading to large errors in the path. These patients cannot anticipate and correct for the intersegmental dynamics that occur around the path reversal. (Reproduced, with permission, from Sainburg et al.1995.)	乏本体感觉输入的受试者中，关节反转的时机不佳，导致运动轨迹出现较大误差。这些患者无法预测和纠正围绕路径反转发生的节间动态。（经授权转载自 Sainburg 等人，1995 年）。
An Overall View	总概
The primary purpose of the elaborate information processing and storage that occurs in the brain is to enable us to interact with our environment. Our infinitely varied and purposeful motor behaviors are governed by the integrated actions of the brain's several motor systems.	大脑精心处理和存储信息的主要目的是使我们能够与环境互动。我们千变万化、目的明确的运动行为受大脑多个运动系统综合作用的支配。
To control action the central nervous system uses a sequence of sensorimotor transformations that convert incoming sensory information into motor outputs. The brain uses internal models at each stage in the sensorimotor transformation. Variability in the inputs and outputs of these transformations and inaccuracies in their representation underlie the errors and variability in movement and lead to the ubiquitous trade-off between speed and accuracy.	为了控制动作，中枢神经系统使用了一连串的感觉运动转换，将传入的感觉信息转换为运动输出。大脑在感觉运动转换的每个阶段都使用内部模型。这些转换的输入和输出的可变性及其表示的不准确性是运动中的误差和可变性的基础，并导致速度和准确性之间无处不在的权衡。
The motor systems generate commands using feedforward circuits or error-correcting feedback circuits; most movement involves both types of control. The adverse effects of delays in feedback are reduced through the use of predictive	运动系统利用前馈电路或纠错反馈电路产生指令；大多数运动都涉及这两种类型的控制。通过使用预测过程，可以减少反馈延迟的不利影响。

processes.	
Finally, motor control circuits are not static but undergo continual modification and recalibration throughout life. Motor learning improves motor control in novel situations, and different forms of sensory information are vital for learning.	最后，运动控制电路并非一成不变，而是在整个生命过程中不断修正和重新校准。运动学习能提高在新情况下的运动控制能力，而不同形式的感官信息对学习至关重要。
The ease with which we conduct ordinary movements masks the true complexity of the control processes involved. Many factors inherent in sensorimotor control are responsible for this complexity, which becomes clearly evident when we try to build machines that can perform human-like control of movement. Although computers can beat grandmasters at chess, no computer can yet control a robot to manipulate a chess piece with the dexterity of a six-year-old child.	我们做普通动作时的轻松自如掩盖了其中控制过程的真正复杂性。感知运动控制中的许多固有因素是造成这种复杂性的原因，当我们试图制造出能像人类一样控制运动的机器时，这种复杂性就会变得非常明显。虽然计算机可以击败国际象棋大师，但还没有计算机可以控制机器人像六岁儿童那样灵巧地操纵棋子。
Figure 33-1 Motor equivalence. The ability of different motor systems to achieve the same behavior is called motor equivalence. For example, writing can be performed using different parts of the body. The examples here were written by the same person using the right (dominant) hand (A), the right hand with the wrist immobilized (B), the left hand (C), the pen gripped between the teeth (D), and the pen attached to the foot (E).(Reproduced, with permission, from Raibert 1977.)	图 33-1 运动等效性 不同运动系统实现相同行为的能力称为运动等效性。例如，书写可以使用身体的不同部位。这里的例子是同一个人使用右手（主手）（A）、手腕固定的右手（B）、左手（C）、夹在牙齿间的笔（D）和连接在脚上的笔（E）书写的。(经授权转载自 Raibert 1977）。
A. Right hand	A.右手

B. Right hand (wrist fixed)	B.右手(手腕固定)
C. Left hand	C.左手
D. Teeth	D.牙齿
A. Locate hand and cup (egocentric coordinates)	A.确定手和杯的位置（自我中心坐标）
B. Plan hand movement (endpoint trajectory)	B.计划手部运动（终点轨迹）
C. Determine intrinsic plan (joint trajectory)	C.确定内在计划（关节轨迹）
D. Execute movement (joint torques)	D.执行动作（关节扭矩）
Figure 33-2 Sensorimotor transformations used to generate a particular movement. The task of generating a goal-directed movement is often broken down into a set of sequential stages, the details of which are still being elucidated. The figure shows one possible set of stages to generate a reaching movement, and the arrows indicate the processes required to move between the stages.	图 33-2 用于产生特定动作的感觉运动转换。产生一个目标指向性动作的任务通常被分解为一系列连续的阶段，其细节仍在研究之中。图中显示了产生伸手动作的一组可能的阶段，箭头表示在各阶段之间移动所需的过程。
A. Spatial orientation. To reach for an object, the object and hand are first located visually in a coordinate system relative to the head (egocentric coordinates). B. Movement planning. The direction and distance the hand must move to reach the object (the endpoint trajectory) are determined based on visual and proprioceptive information about the current locations of the arm and object. C. Inverse kinematic transformation.	A.空间定向。要伸手去拿一个物体，首先要在相对于头部的坐标系（自我中心坐标）中对物体和手进行视觉定位。B.运动规划。根据手臂和物体当前位置的视觉和本体感觉信息，确定手伸向物体的方向和距离（端点轨迹）。C.逆运动学转换。确定实现手部路径的关节轨迹。从所需的手部运动到关节轨迹的转换取决于手臂的运动学特性，如手臂各节的长度。D.逆动态变换。确定实现所

The joint trajectories that will achieve the hand path are determined. The transformation from a desired hand movement to the joint trajectory depends on the kinematic properties of the arm, such as the lengths of the arm's segments. D. Inverse dynamic transformation. The joint torques or muscle activities that are necessary to achieve the desired joint trajectories are determined. The joint torques required to achieve a desired change in joint angles depend on the dynamic properties of the arm such as the mass of the segments.	需关节轨迹所需的关节扭矩或肌肉活动。实现所需的关节角度变化所需的关节扭矩取决于手臂的动态特性，如各节的质量。
Figure 33-3 Internal models represent relationships of the body and external world. The inverse model determines the motor commands that will produce a behavioral goal, such as raising the arm while holding a ball. A descending motor command acts on the musculoskeletal system to produce the movement. A copy of the motor command is passed to a forward model that simulates the interaction of the motor system and the world and can therefore predict behaviors. If both forward and inverse models are accurate, the output of the forward model (the predicted behavior) will be the same as the input to the inverse model (the desired behavior).	图 33-3 内部模型表示身体与外部世界的关系。逆向模型决定产生行为目标的运动指令，例如在抱球时抬起手臂。下行运动指令作用于肌肉骨骼系统以产生运动。运动指令的副本会传递给前向模型，该模型模拟运动系统与世界的交互，从而预测行为。如果正向模型和逆向模型都准确无误，那么正向模型的输出（预测行为）将与逆向模型的输入（期望行为）相同。
Figure 33-4 Accuracy of movement varies in	图 33-4 运动的准确性与速度成正

direct proportion to its speed. Subjects held a stylus and were required to try and hit a target line lying perpendicular to the direction in which they moved. Each subject started from three different initial positions and was required to complete the movement within three different times (140, 170, or 200 ms). A successful trial was one in which the subject completed the movement within 10% of the required time. Only successful trials were used for analysis. Subjects were informed if their movements were more than 10% different from the required duration.	比。受试者手持测针，需要尝试击中与其移动方向垂直的目标线。每个受试者从三个不同的初始位置开始，要求在三个不同的时间（140、170 或 200 毫秒）内完成运动。受试者在规定时间的10%内完成动作即为成功试验。只有成功的试验才用于分析。如果受试者的动作与规定时间相差超过 10%，会有人告知该受试者。
The plot shows the variability in the motion of the subjects* arm movements as the standard deviation of the extent of movement versus average speed (for each of three movement starting points and three movement times, giving nine data points). The variability in movement increases in proportion to the speed and therefore to the force producing the movement. (Reproduced, with permission, from Schmidt et al.1979.)	**下图的 9 个数据点，即运动幅度与平均速度的标准偏差，其中包括 3 个运动起点和 3 个运动时间。这 9 个数据点显示了受试者*手臂运动的变异性。**运动的可变性与速度成正比，因此也与产生运动的力量成正比。(经许可，转载自施密特等人，1979 年)。
Figure 33-5 The location of the finger in space can be specified in different egocentric coordinate systems.	图 33-5 手指在空间中的位置可以在不同的自我中心坐标系中指定。
A. Cartesian coordinates centered on the eyes.	A.以眼睛为中心的直角坐标系。
B. Spherical polar coordinates centered on the shoulder (distance, azimuth, and elevation)	B. 以肩部为中心的球面极坐标（距离、方位角和仰角）
C. An intrinsic coordinate system based on	C.基于肩角（a1 和 a2）和肘角

shoulder angles (a1, and a2), which relate the orientation of the upper arm to the Cartesian axes, and elbow angle (a3), which specifies the angle between the upper and lower arm.	（a3）的固有坐标系，肩角表示上臂与笛卡尔坐标轴的方向，肘角表示上臂与下臂的夹角。
Figure 33-6 Errors in distance and direction of movement are independent of each other. Distribution of endpoints for reaching movements to 16 targets (eight directions and two distances) by one subject. Targets (red circles) were presented 24 times in random order, and each time the subject was asked to place a finger on the target. All movements begin from a central starting position (designated+). Endpoints for individual movements are represented by blue dots. The endpoints for the reaches to each target are fitted with an ellipse, demonstrating that errors in distance and direction are independent of each other. (Adapted, with permission, from Gordon, Ghilardi, and Ghez 1994.)	图 33-6 运动距离和方向的误差是相互独立的。一名受试者向 16 个目标（8 个方向和 2 个距离）伸手运动的终点分布。目标（红色圆圈）以随机顺序出现 24 次，每次要求受试者将手指放在目标上。所有动作都从一个中心起始位置（指定+）开始。单个动作的终点用蓝点表示。到达每个目标的终点都用一个椭圆拟合，表明距离和方向的误差是相互独立的。(经许可，改编自 Gordon、Ghilardi 和 Ghez 1994）。
Figure 33-7 Distance errors are greater than direction errors for movements in the dark. A subject was asked to place a finger on the remembered location of a target in the dark. Final finger position and target location are plotted in spherical coordinates centered on the shoulder (see Figure 33-5B). The straight line represents perfect performance and the dots individual reaching movements. Radial distance errors and angular errors (azimuth and elevation) are plotted separately.	图 33-7 黑暗中运动的距离误差大于方向误差。要求受试者在黑暗中将手指放在记忆中的目标位置上。最终手指位置和目标位置以肩部为中心绘制成球形坐标（见图 33-5B）。直线代表完美表现，圆点代表个别伸手动作。径向距离误差和角度误差（方位角和仰角）分别绘制。(经许可，改编自 Soechting 和 Flanders 1989）。

(Adapted, with permission, from Soechting and Flanders 1989.)	
Figure 33-8 Fitts's law describes the speed-accuracy trade-off. Subjects were required to move a stylus between two targets of width UV separated by distance A The width of the targets was changed on each trial. Each line in the plot represents the results for a different target width (from narrow to wide) over four different movement amplitudes. Subjects were required to move as fast as possible while still hitting the targets. Over a large range of target widths and distance between targets, movement duration is linearly dependent on log2[2AIW), the index of difficulty. (Adapted, with permission, from Jeannerod 1988.)	图 33-8 菲茨定律描述了速度与精确度之间的权衡。受试者需要在距离 A 相隔的两个宽度为 UV 的目标之间移动测针。图中的每一条线都代表了不同目标宽度（从窄到宽）在四种不同移动幅度下的结果。受试者需要在击中目标的同时尽可能快地移动。在目标宽度和目标间距离的较大范围内，运动持续时间与难度指数 log2[2AIW] 呈线性关系。(经许可，改编自 Jeannerod 1988)。
Figure 33-9 Hand path and velocity have stereotypical features. (Adapted, with permission, from Morasso 1981.) A. The subject sits in front of a semicircular plate and grasps the handle of a two-jointed apparatus that moves in one plane and records hand position. The subject is instructed to move the hand between various targets (T1-T6). The record on the right shows the paths traced by one subject. B. Kinematic data for three hand paths shown in part A (c, d, and e). All paths are roughly straight, and all hand speed profiles have the same shape and scale in proportion	"图 33-9 手的运动轨迹和速度具有刻板特征。(经许可，改编自 Morasso 1981)。 A.受试者坐在一个半圆形板前，抓住一个双关节仪器的手柄，该仪器在一个平面内移动并记录手的位置。受试者被指示在不同的目标（T1-T6）之间移动手。右侧的记录显示了一名受试者的移动路径。 B. A 部分（c、d 和 e）所示三条手部路径的运动轨迹数据。所有

to the distance covered. In contrast, the profiles for the angular velocity of the elbow and shoulder for the three hand paths differ. The straight hand paths and common profiles for speed suggest that planning is done with reference to the hand because these parameters can be linearly scaled. Planning with reference to joints would require computing nonlinear combinations of joint angles.	路径都大致呈直线，所有手速曲线的形状和比例都与所覆盖的距离成正比。相比之下，三条路径的肘部和肩部角速度曲线则有所不同。笔直的手部运动轨迹和共同的速度曲线表明，规划是以手部为参考进行的，因为这些参数可以线性缩放。而参照关节进行规划则需要计算关节角度的非线性组合"。
Figure 33-10 Complex movements obey the two-thirds power law. (Reproduced, with permission, from Lacquaniti, Terzuolo, and Viviani 1983.) A. Nondirected scribbling is a complex movement. B. Instantaneous values of the angular velocity of the hand while scribbling are plotted against the curvature of the hand's path raised to the power of two-thirds. The relation between the two variables is piecewise linear. Each segment in the bundle, corresponding to nonoverlapping segments of the trajectory, has a different slope. The slopes cluster around the average (dashed line), a typical result for this type of experiment. Therefore, the relationship between the speed of hand motion and the degree of curvature of the hand path is roughly constant: Velocity varies as a	图 33-10 复杂运动遵循三分之二幂律。(经授权转载自 Lacquaniti、Terzuolo 和 Viviani 1983)。 A.非定向涂鸦是一种复杂运动。 B.涂鸦时手部角速度的瞬时值与手部路径曲率的三分之二幂的关系图。两个变量之间是片断线性关系。线束中的每个线段（对应于轨迹的非重叠线段）都有不同的斜率。斜率集中在平均值（虚线）附近，这是此类实验的典型结果。因此，手部运动速度与手部轨迹曲率之间的关系大致恒定：速度的变化是曲率上升到三分之二幂的连续函数。这个三分之二幂定律几乎适用于所有运动，它表示在弯曲度较大的运动

continuous function of the curvature raised to the power of two-thirds. This two-thirds power law governs virtually all movements and expresses an obligatory slowing of the hand during movement segments that are more curved and a speeding up during segments that are straight. Because angular velocity is the speed of the hand multiplied by the path curvature, in the plot an increase in angular velocity represents a decrease in hand speed.	段中，手的速度必须减慢，而在弯曲度较小的运动段中，手的速度则必须加快。在弯曲较多的运动片段中，手的速度必然减慢，而在直线运动片段中，手的速度必然加快。由于角速度是手的速度乘以路径曲率，因此在图中，角速度的增加代表手速的降低。
Figure 33-11 Feedforward and feedback control. A. A feedforward controller generates a motor command based on a desired state. Any errors that arise during the movement are not monitored. B. **With feedback control the desired and sensed states are compared (at the comparator) to generate an error signal, which helps shape the motor command.** There can be considerable delay in the feedback of sensory information to the comparator.	图 33-11 前馈和反馈控制 A.前馈控制器根据预期状态生成电机指令。运动过程中出现的任何错误都不会受到监控。 B.**在反馈控制中，预期状态和感知状态通过比较器进行比较，以产生误差信号，从而形成电机指令。**感知信息反馈到比较器可能会有相当大的延迟。
Figure 33-12 Acceleration and velocity of reaching are a function of target distance. (Modified, with permission, from Gordon et al.1994.) A. Hand paths measured to targets located 2.5, 5, 10, 20, and 30 cm from the starting	"图 33-12 伸手的加速度和速度是目标距离的函数。(经许可，改编自 Gordon 等人，1994 年）。 A.从起始位置到目标点 2.5、5、10、20 和 30 厘米处所测得的手部

position. B. Average velocity and acceleration of the hand movements shown in part A. The acceleration and velocity profiles scale linearly as a function of the distance to the target. All the velocity profiles are self-similar and when normalized in time and amplitude are nearly identical. The single peaks indicate that the extent of movement is specified prior to actual movement. If it were not, the first peak would be the same for all target distances, and secondary peaks representing feedback adjustment would be seen.	路径。 B.加速度和速度曲线与目标距离成线性关系。所有速度曲线都是自相似的，在时间和振幅上归一化后几乎相同。单个峰值表明，在实际运动之前，运动范围已经确定。否则，所有目标距离的第一个峰值都是相同的，而且会出现代表反馈调整的次要峰值"。
Figure 33-13 The interplay of gain and delay in feedback control. Subjects use a controller to track a target moving sinusoidally in one dimension. The sensory feedback signal that conveys error in the hand's position arrives after some period of time (the delay), and the motor system tries to correct for the error by increasing or decreasing the size of its command relative to the error (the gain). The plots show the performance of a subject tracking a sinusoidal target in which there is either instantaneous feedback of error (left column) or feedback with a delay (middle and right columns). When the gain is high, and the delay is low, tracking is very good. However, as the delay increases, the motor system corrects for error inappropriately, and this leads to oscillations and large errors.	"图 33-13 增益和延迟在反馈控制中的相互作用。受试者使用控制器追踪在一维范围内正弦运动的目标。传递手部位置误差的感觉反馈信号会在一段时间后到达（延迟），运动系统会尝试通过增加或减少与误差相关的指令大小（增益）来修正误差。图中显示的是受试者在跟踪正弦波目标时的表现，其中既有瞬时误差反馈（左列），也有延迟反馈（中间和右列）。当增益高、延迟低时，跟踪效果非常好。然而，随着延迟的增加，电机系统对误差的修正会变得不恰当，从而导致振荡和较大的误差。为了保持

To maintain stability, the gain can be lowered, but tracking is not perfect. At low gain (bottom row) the feedback controller corrects errors only slowly and tracking is inaccurate. As the gain increases (middle row) the feedback controller corrects errors more rapidly and tracking performance improves. At high gain (top row) the system corrects rapidly but is prone to overcorrect, leading to instability when the time delay in feedback is on the order of physiological time delays (top right). Because the controller is compensating for errors that existed 100 ms earlier, the correction may therefore be inappropriate for the current error. This overcorrection leads to oscillations and is one mechanism proposed to account for some forms of oscillatory tremor seen in neurological disease.	稳定，可以降低增益，但跟踪效果并不完美。增益较低时（下行），反馈控制器的误差修正速度较慢，跟踪不准确。随着增益的增加（中间一行），反馈控制器纠错速度加快，跟踪性能提高。当增益较高（上排）时，系统纠错速度快，但容易出现过度纠错，当反馈的时间延迟与生理时间延迟相当时，系统就会出现不稳定（右上角）。由于控制器是在补偿100毫秒前存在的误差，因此修正可能不适合当前的误差。这种过度校正会导致振荡，这也是神经疾病中某些振荡性震颤的一种机制。
Figure 33-14 Both feedback and feedforward controls are used when lifting an object A. The subject lifts an object from the table. Sensory receptors measure vertical motion, grip force, and the load force applied to the object to overcome gravity and inertia. The discharge of different sensory receptors is recorded by microelectrodes inserted within identified sensory axons of the peripheral nerve, a procedure called microneurography. B. When the subject knows the weight of the object in advance, the applied forces	图 33-14 提升物体时会同时使用反馈和前馈控制。 A.实验对象从桌面上提起一个物体。感觉器测量垂直运动、握力以及施加到物体上以克服重力和惯性的负荷力。不同感觉感受器的放电通过插入周围神经感觉轴突内的微电极进行记录，这一过程称为微神经电图。 B.当受试者事先知道物体的重量时，施加的力足以将物体举起。

are adequate to lift the object. Three sets of traces (24 trials superimposed) show load force, grip force, and position as subjects lifted three objects of different weights (200, 400, and 800 g). The grip force increases in proportion to the weight of the object. This is done by scaling a preprogrammed force profile (the profiles have the same shape but different amplitudes). C. When the weight is larger than expected, the object slips initially, but force is increased before lifting begins. When the subject begins to lift a 400 g object, Pacinian corpuscles in the skin are activated and a burst of action potentials occurs in the afferent **RA2 fibers**, signaling the beginning of the hold phase during which the grip force is constant. After being presented with the 400 g object for several trials (dashed lines), the subject is given an 800 g object (solid lines). When the subject begins to lift the 800 g object, the object slips, and the **RA2 fibers** are not activated. The absence of **RA2 signals** triggers a slow increase in force that is terminated when lifting begins. （Reproduced, with permission, from Johansson et al.1991.)	三组轨迹（24 次试验叠加）显示了受试者举起三个不同重量（200、400 和 800 克）物体时的负荷力、握力和位置。这是通过缩放预先编程的力曲线实现的（曲线形状相同，但振幅不同）。 C.当重量大于预期时，物体最初会滑落，但在开始举起之前力会增加。当受试者开始举起一个 400 克的物体时，皮肤中的帕氏体被激活，传入**快适应感受器二类（RA2）纤维**出现动作电位爆发，标志着握力恒定的保持阶段开始。在对 400 克的物体进行多次试验后（虚线），受试者会得到一个 800 克的物体（实线）。当受试者开始举起 800 克的物体时，物体滑落，**快适应感受器二类（RA2）纤维**没有被激活。**快适应感受器二类（RA2）信号**的缺失引发了力量的缓慢增加，当开始举起时，力量的增加被终止。（经许可，转自 Johansson 等人，1991 年）"
Figure 33-15 An observer model. The drawing shows how the finger's location can	图 33-15 观察者模型图中显示了在手臂运动过程中如何估算手指

be estimated during movement of the arm. A previous estimate of the distribution of possible finger positions (1) is the basis for a new estimate (2). This estimation uses an efference copy of the motor command and a model of the dynamics. The new distribution of estimated finger positions (the "cloud of uncertainty") is larger than that of the previous estimate. The model then predicts the sensory feedback that would occur for these new finger positions, and the error between the predicted and actual sensory feedback is used to correct the estimate of current finger position. This correction changes the sensory error into state errors and also determines the relative reliance on the efference copy and sensory feedback. The final estimate of current finger position (3) has less uncertainty. This estimate becomes the new previous estimate for subsequent movement as this sequence is repeated many times. Delays in sensory feedback that must be compensated have been omitted from the diagram for clarity.	的位置。先前对手指可能位置分布的估算（1）是新估算（2）的基础。这种估算使用的是运动指令的有效副本和动态模型。新的估算手指位置分布（"不确定性云"）大于之前的估计。然后，模型会预测这些新的手指位置所产生的感觉反馈，并利用预测和实际感觉反馈之间的误差来修正当前手指位置的估算值。这一修正将感官误差转化为状态误差，同时也决定了对效能副本和感官反馈的相对依赖程度。当前手指位置的最终估算值(3)的不确定性较小。随着这一序列的多次重复，这一估算值将成为后续运动的新的先前估算值。为清晰起见，图中省略了必须补偿的感觉反馈延迟。
Figure 33-16 Anticipatory control of self-generated actions. (Reproduced, with permission, from Blakemore, Goodbody, and Wolpert 1998.) A. When a subject is instructed to hold onto an object to which a robort is applying a sinusoidal load force, the grip force of the fingers is high to prevent slippage but nevertheless lags behind the increases in load force.	图 33-16 自我产生动作的预期控制。(A.当受试者被指示握住一个物体时，机器人会施加一个正弦负荷力，手指的握力会很高以防止滑动，但仍会滞后于负荷力的增加。B.相反，当被试主动向下拉动物体，产生类似的负载曲线时，负载力是可以预期的，因此

B. Conversely, when the subject actively pulls down the object, producing a similar load profile, the load force can be anticipated and thus the grip force is lower and tracks the load force without delay.	抓力较小，并能毫不迟疑地跟踪负载力。
Figure 33-17 The size-weight illusion. (Reproduced, with permission, from Flanagan and Beltzner 2000.) A. In each trial subjects lifted first a large object and then a small object that weighed the same. Subjects thought the smaller object felt heavier than it actually was. B. In the first trial subjects generated greater grip and load forces for the bigger object (orange traces) as it was expected to be heavier than the small object. In the eighth trial the grip and load forces are the same for the two objects, showing that the sensorimotor system generates grip and load forces appropriate to the weights of the two objects despite the conscious perception of a difference in weight.	"图 33-17 大小-重量错觉。(经授权转载自 Flanagan 和 Beltzner 2000） A.在每次试验中，受试者先举起一个大物体，然后再举起一个重量相同的小物体。受试者认为小物体比实际重。 B.在第一次试验中，受试者对较大物体（橙色痕迹）产生了更大的抓握力和负载力，因为预期它比小物体重。在第八次试验中，两个物体的握力和负载力相同，这表明尽管有意识地感觉到两个物体的重量不同，但感觉运动系统仍会产生与两个物体重量相适应的握力和负荷力"。
Figure 33-18 Learning improves the accuracy of reaching in a novel dynamic environment. A. A subject holds an apparatus that measures the position and velocity of the hand and applies forces to the hand. (Reproduced, with permission, from Brashers-Krug, Shad Mehr, and Bizzi 1996.)	图 33-18 在新颖的动态环境中，学习提高了伸手的准确性。A.受试者手持一个仪器，该仪器可显示手的位置和速度，并对手部施加力。（经授权，转载自 Brashers-Krug 、 Shad Mehr 和 Bizzi 1996。）

B. When the motors are off (null field) the subject makes approximately straight movements from the center of the workspace to targets arrayed in a circle. C. A clockwise force is then applied to the hand, shown as a function of hand velocity. This field produces a force proportional to the speed of the hand that always acts at right angles to the current direction of motion. D. Initially the hand paths are severely perturbed in response to the perturbing force (1). After some time, the subject adapts and can again follow a straight path during the entire movement (2). When the motors are then turned off, movement is again perturbed but, in a direction, opposite to the earlier perturbation (3).	B.当电机关闭时（空场），被试从工作区中心向一圈内的目标做近似直线运动。 C.然后向手部施加顺时针方向的力，如图所示为手部速度的函数。该场产生的力与手的速度成正比，始终与当前运动方向成直角。 D.最初，手的运动轨迹会受到扰动力(1)的严重干扰。一段时间后，受试者就会适应，并在整个运动过程中再次沿直线运动(2)。然后关闭电机，运动再次受到扰动，但方向与之前的扰动相反（3）。
Figure 33-19 Patients lacking proprioception cannot maintain internal models of limb inertia. A. Accuracy and trajectory control decay rapidly when patients cannot see their limbs. A patient with large-fiber sensory neuropathy, with no sense of position in the arm for several years, moved a mouse-like cursor repeatedly from a starting position to a target displayed on a computer screen in front of her. When the patient was able to see the screen cursor and her hand,	图 33-19 缺乏本体感觉的患者无法维持肢体惯性的内部模型。 A.当患者看不到自己的肢体时，精确度和轨迹控制会迅速下降。一位患有大纤维感觉神经病变的患者，其手臂数年来一直没有位置感，她将一个类似鼠标的光标从起始位置反复移动到面前电脑屏幕上显示的目标。当患者能够看到屏幕光标和她的手时，移动是笔直的，而且相当准确（1）。

movements were straight and reasonably accurate (1). Movements become increasingly curved and inaccurate after vision of her arm was removed for 2 minutes (2) and 6 minutes (3). (Reproduced, with permission, from Ghez, Gordon, and Ghilardi 1995.) B. A patient without proprioception plans movement without taking account of variations in limb inertia. Patients and normal subjects were instructed to move a finger to 22 targets arranged concentrically. Subjects were prevented from seeing their limb. (1) Movements made by a control subject are straight and evenly distributed throughout the workspace.(2) Movements made by a patient with loss of limb proprioception vary in extent in different directions. The variation in extent is explained by the fact that directional changes in inertia vary with movement direction according to an elliptical contour (inertia ellipse). This means that a constant initial force at the hand will accelerate the limb differently in different directions (mobility ellipse); high acceleration occurs in directions that have low inertia. The mobility computed for the subject^ arm plotted over the hand paths shown at left closely matches the variations in movement extent. (Reproduced, with permission, from Gordon, Ghilardi, and Ghez 1995.)	当她的手臂视线被遮挡 2 分钟（2）和 6 分钟（3）后，动作变得越来越弯曲和不准确。(经授权转载自 Ghez、Gordon 和 Ghilardi 1995）。 B.没有本体感觉的患者在不考虑肢体惯性变化的情况下计划运动。患者和正常受试者被要求移动手指到 22 个同心排列的目标上。受试者无法看到自己的肢体。(1)对照组受试者的移动是直线的，并均匀分布在整个工作区。(2)肢体本体感觉缺失患者在不同方向上的移动幅度不同。惯性的方向性变化根据椭圆轮廓（惯性椭圆）随运动方向的变化而变化。这意味着手部恒定的初始力会在不同方向上对肢体产生不同的加速度（活动度椭圆）；惯性小的方向加速度大。根据左图所示的手部运动轨迹计算出的受试者^手臂的活动度与运动幅度的变化非常吻合。(经许可，转载自 Gordon、Ghilardi 和 Ghez 1995）"

Figure 33-20 Patients lacking proprioception cannot make an accurate movement that requires a rapid reversal in path. In normal subjects the joint angles for the elbow and shoulder show good alignment, leading to an accurate reversal. In subjects who lack proprioceptive input the timing of the joint reversal is poor, leading to large errors in the path. These patients cannot anticipate and correct for the intersegmental dynamics that occur around the path reversal. (Reproduced, with permission, from Sainburg et al.1995.)	图 33-20 缺乏本体感觉的患者无法做出需要快速反转路径的准确动作。在正常人身上，肘部和肩部的关节角度显示出良好的对齐，从而导致准确的反转。在缺乏本体感觉输入的受试者中，关节反转的时机不佳，导致运动轨迹出现较大误差。这些患者无法预测和纠正围绕路径反转发生的节间动态。(经授权，转载自 Sainburg 等人，1995 年)。

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