

---

---

**Robotics — Performance criteria  
and related test methods for service  
robots —**

**Part 4:  
Lower-back support robots**

*Robotique — Critères de performance et méthodes d'essai  
correspondantes pour robots de service —*

*Partie 4: Robots de soutien du bas du dos*

STANDARDSISO.COM : Click to view the full PDF of ISO 18646-4:2021



STANDARDSISO.COM : Click to view the full PDF of ISO 18646-4:2021



**COPYRIGHT PROTECTED DOCUMENT**

© ISO 2021

All rights reserved. Unless otherwise specified, or required in the context of its implementation, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office  
CP 401 • Ch. de Blandonnet 8  
CH-1214 Vernier, Geneva  
Phone: +41 22 749 01 11  
Email: [copyright@iso.org](mailto:copyright@iso.org)  
Website: [www.iso.org](http://www.iso.org)

Published in Switzerland

# Contents

	Page
<b>Foreword</b> .....	<b>iv</b>
<b>Introduction</b> .....	<b>v</b>
<b>1 Scope</b> .....	<b>1</b>
<b>2 Normative references</b> .....	<b>1</b>
<b>3 Terms and definitions</b> .....	<b>1</b>
<b>4 Test conditions</b> .....	<b>3</b>
4.1 General.....	3
4.2 Environmental conditions.....	3
4.3 Operating conditions.....	4
<b>5 Test method for assistive torque index and lumbar compression reduction</b> .....	<b>4</b>
5.1 Purpose.....	4
5.2 Relevant characteristics.....	4
5.2.1 General.....	4
5.2.2 Assistive torque index (ATI).....	4
5.2.3 Lumbar compression reduction (LCR).....	5
5.3 Test facility.....	7
5.3.1 Test apparatus.....	7
5.3.2 Reference movement and target trajectory.....	8
5.4 Test procedure.....	10
5.5 Test result.....	11
<b>6 Test method for rate of assistance</b> .....	<b>11</b>
6.1 Purpose.....	11
6.2 Relevant characteristics.....	11
6.3 Test facility.....	12
6.4 Test procedure.....	15
6.5 Test result.....	18
<b>Annex A (informative) Time range of ATI and LCR</b> .....	<b>19</b>
<b>Annex B (informative) Example of lower-back support robots</b> .....	<b>23</b>
<b>Annex C (informative) Example table of test results</b> .....	<b>25</b>
<b>Annex D (informative) Example implementation of a test apparatus</b> .....	<b>26</b>
<b>Bibliography</b> .....	<b>29</b>

## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see [www.iso.org/directives](http://www.iso.org/directives)).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see [www.iso.org/patents](http://www.iso.org/patents)).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see [www.iso.org/iso/foreword.html](http://www.iso.org/iso/foreword.html).

This document was prepared by Technical Committee ISO/TC 299, *Robotics*.

A list of all parts in the ISO 18646 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at [www.iso.org/members.html](http://www.iso.org/members.html).

## Introduction

This document is intended to facilitate understanding of performance of lower-back support robots (see [Annex B](#)). This document defines the important performance characteristics and describes how to specify them and how to test them.

The characteristics for which test methods are given in this document are those considered to affect robot performance significantly. The user of this document selects which performance characteristics to test, in accordance with the specific requirements.

The performance criteria specified in this document are not intended to be interpreted as the verification or validation of safety requirements. The verification and validation of safety requirements are specified in other standards developed by ISO TC 299.

The International Organization for Standardization (ISO) draws attention to the fact that it is claimed that compliance with this document may involve the use of patents concerning the test apparatuses of the performance of wearable robots for lower-back support referred to throughout the document.

ISO takes no position concerning the evidence, validity and scope of these patent rights.

The holders of these patent rights have assured ISO that they are willing to negotiate licences under reasonable and non-discriminatory terms and conditions with applicants throughout the world. In this respect, the statements of the holders of these patent rights are registered with ISO. Information may be obtained from the patent database available at [www.iso.org/patents](http://www.iso.org/patents).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights other than those in the patent database. ISO shall not be held responsible for identifying any or all such patent rights.

STANDARDSISO.COM : Click to view the full PDF of ISO 18646-4:2021

# Robotics — Performance criteria and related test methods for service robots —

## Part 4: Lower-back support robots

### 1 Scope

This document describes methods of specifying and evaluating the performance of lower-back support robots.

This document applies regardless of the purpose and application of lower-back support robots and the driving methods (e.g. electric, hydraulic and pneumatic). This document does not apply to medical robots, although the test methods specified in this document can be utilized for medical robots.

This document is not intended for the verification or validation of safety requirements.

### 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 8373, *Robots and robotic devices — Vocabulary*

ISO 13482, *Robots and robotic devices — Safety requirements for personal care robots*

### 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 8373, ISO 13482 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

#### 3.1

##### **robot**

programmed actuated mechanism with a degree of autonomy, moving within its environment, to perform intended tasks

Note 1 to entry: A robot includes the control system and interface of the control system.

Note 2 to entry: The classification of robot into industrial robot or service robot is done according to its intended application.

[SOURCE: ISO 8373:2012, 2.6, modified — The words “actuated mechanism programmable in two or more axes” have been replaced with “programmed actuated mechanism”.]

### 3.2

#### **wearable robot**

robot that supplements or augments personal capabilities while attached to a human during use

Note 1 to entry: Wearable robots are referred to as restraint-type physical assistant robots in ISO 13482:2014.

### 3.3

#### **lower-back support robot**

wearable robot to reduce the load in the lower back of the user by its assistive force or torque

### 3.4

#### **user**

person who wears a wearable robot on his/her body and directly receives its assistive force or torque

### 3.5

#### **restraint part**

part of the wearable robot binding a corresponding attached body part of the user to transmit an assistive force or torque

### 3.6

#### **assistive torque**

output torque of the wearable robot to assist a user to perform required tasks

### 3.7

#### **attached body part**

part of the user's body on which the restraint part of the wearable robot is attached

### 3.8

#### **input method**

interface allowing the user to control the assistive force or torque of the wearable robot by an appropriate input signal

#### 3.8.1

##### **biological input**

input method where biological signals that are in correlation to the force or torque the user exerts at his/her body part intended for assistance are used as the input

Note 1 to entry: Biological signals include bioelectrical signals such as myoelectric signals.

#### 3.8.2

##### **kinematic input**

input method where movement and/or posture of the user's body parts intended for assistance are used as the input

Note 1 to entry: Biological input and kinematic input are mutually exclusive.

#### 3.8.3

##### **command input**

any input method other than biological input or kinematic input

Note 1 to entry: Command input includes the use of commanding devices, breath switches or voice input.

Note 2 to entry: Command input includes the use of biological signals that are not in correlation to the force or torque the user exerts at the body part intended for assistance.

Note 3 to entry: Command input includes movement and/or posture of the user's body parts not intended for assistance.

### 3.9 assistive torque index ATI

measure of how much the output torque of the user is reduced when the user performs a specific movement during a specific time range using the lower-back support robot

Note 1 to entry: ATI is an absolute quantity with respect to the average torque during the specific time period of a specific test motion profile. It can be helpful for the relative comparison between robots.

### 3.10 lumbar compression reduction LCR

measure of how much the compressive force on the user's lumbar disks is reduced when the user performs a specific movement during a specific time range using the lower-back support robot

### 3.11 normal operating conditions

range of environmental conditions and other parameters which can influence robot performance (such as electrical supply instability, electromagnetic fields) within which the performance of the robot specified by the manufacturer is valid

Note 1 to entry: Environmental conditions include, for example, temperature and humidity.

[SOURCE: ISO 8373:2012, 6.1]

### 3.12 rate of assistance

measure of the reduced torque by a lower-back support robot integrated over the time period of a specific test motion profile

Note 1 to entry: Rate of assistance is a normalized quantity with respect to the integrated torque over the time period of a specific test motion profile. It can be helpful for the relative comparison for different test motion profiles within the robot.

## 4 Test conditions

### 4.1 General

The lower-back support robot shall be completely assembled, sufficiently charged and operational. All self-diagnostic tests shall be satisfactorily completed. It should also be ensured that the robot operates in a safe manner throughout the test.

The tests shall be preceded by the preparations for operation as specified by the manufacturer, including calibration of any relevant sensors that effect on the test results.

All conditions specified in [Clause 4](#) should be satisfied for the tests described in this document, unless it is stated otherwise in the specific clauses.

Each test described in [Clause 5](#) and [Clause 6](#) of this document have different test configurations which require separate test apparatuses and test procedures.

### 4.2 Environmental conditions

The following environmental conditions shall be maintained during all tests.

- Ambient temperature: 10 °C to 30 °C
- Relative humidity: 0 % to 80 %

If the environmental conditions specified by the manufacturer are outside the given conditions, then this shall be declared in the test results.

### 4.3 Operating conditions

All performance shall be measured under normal operating conditions. When the performance is measured under conditions outside the normal operating conditions, these conditions shall be specified along with the test results.

## 5 Test method for assistive torque index and lumbar compression reduction

### 5.1 Purpose

This clause describes the method of specifying and evaluating the performance of lower-back support robots.

NOTE Theoretical backgrounds and validation experiments are provided in Reference [6] which provides a rationale of focusing only on bending torques and compression forces. At the current stage of the market, there are only the products that are intended to assist sagittal movement. To keep the test apparatus and test method simple, the limitation of the test method is considered acceptable to measure a representative performance of the robots.

### 5.2 Relevant characteristics

#### 5.2.1 General

Two performance indices are introduced for this test method: Assistive torque index (ATI) and Lumbar compression reduction (LCR).

By the assistive torque of the robot, the user's extension force of hip joints and that of the trunk will be reduced, and then the compressive force on lumbar disks will be reduced. Ideally, the lumbar compression can be derived from the extension torque of hip joints and the posture of the trunk. The extension torque can be reduced by the assistive torque of the robot. For the robot with such characteristics, the lumbar compression does not need to be measured because it can be inferred from the assistive torque and the posture of trunk.

For some robots for which lumbar compression could be increased because of the robot's mechanical structure, mass and mass distribution above the lumbar joint and/or actuation method (e.g. artificial muscles on user's back skin), lumbar compression should be measured together with assistive torque.

NOTE According to Reference [1], compressive force on lumbar disks can be the major cause of back injury and, therefore, often used as an index to estimate the risk of back injury. Based on this background, LCR is introduced as a performance indication of the robot.

#### 5.2.2 Assistive torque index (ATI)

The Assistive Torque Index (ATI) consists of 5 representative values,  $ATI_{1000}^{Lower}$ ,  $ATI_{200}^{Lower}$ ,  $ATI_{1000}^{Hold}$ ,  $ATI_{1000}^{Raise}$  and  $ATI_{200}^{Raise}$ , which are calculated by the following formulae with  $t_1$  and  $t_2$  specified in

**Table 1.** The superscript and the subscript of ATI indicate a phase of reference movement and a time duration in milliseconds, respectively.

$$ATI_{t_2-t_1}^{\text{ref}} = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} \psi(\tau^{\text{ref}}(t), \tau(t)) dt$$

where

$$\psi(\alpha, \beta) = \begin{cases} \alpha - \beta & \text{if } \alpha \geq 0 \\ -(\alpha - \beta) & \text{if } \alpha < 0 \end{cases}$$

$\tau^{\text{ref}}(t)$  is the actual output torque of the hip joints of the test apparatus (see 5.3.1) during the reference movements (without robot);

$\tau(t)$  is the actual output torque of the hip joints of the test apparatus (see 5.3.1) during the reference movements (with robot).

**NOTE 1** In general, the assistive torque of a robot interferes with the duration of the movement and the necessary force or torque of the user. This is a source of instability of the test results. Therefore, this document adopts a time average within a specific time range during the reference movements.

**NOTE 2** As the reference movements defined in 5.3.2 are antigravity movements,  $\tau^{\text{ref}}(t)$  is expected to be always negative and the relationship  $\psi(\alpha, \beta) = -(\alpha - \beta)$  always applies. However, this document defines  $\psi$  in a more general form to make  $\psi$  positive when the necessary torque for the reference movement and the torque of the robot are in the same direction. See Annex A.

**NOTE 3** When  $\psi$  is positive, the torque of the robot in the antigravity direction (extension) can reduce the necessary torque of the user to achieve the reference movements. Or, in some cases, the user has to output the torque in the gravity direction (flexion) to resist the torque of the robot. When  $\psi$  is negative, the torque of the robot in the gravity direction (flexion) can increase the necessary torque of the user to achieve the reference movements. See Annex A.

### 5.2.3 Lumbar compression reduction (LCR)

The Lumbar Compression Reduction (LCR) consists of 5 representative values  $LCR_{1000}^{\text{Lower}}$ ,  $LCR_{200}^{\text{Lower}}$ ,  $LCR_{1000}^{\text{Hold}}$ ,  $LCR_{1000}^{\text{Raise}}$  and  $LCR_{200}^{\text{Raise}}$ , which are calculated by the following formulae with  $t_1$  and  $t_2$  specified in Table 1. The superscript and the subscript of LCR indicate a phase of reference movement and a time duration in milliseconds, respectively.

$$LCR_{t_2-t_1}^{\text{ref}} = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} \psi(F^{\text{ref}}(t), F(t)) dt$$

where

$$\psi(\alpha, \beta) = \begin{cases} \alpha - \beta & \text{if } \alpha \geq 0 \\ -(\alpha - \beta) & \text{if } \alpha < 0 \end{cases}$$

$$F^{\text{ref}}(t) = \phi(M_y^{\text{ref}}(t)) + F_z^{\text{ref}}(t),$$

$$F(t) = \phi(M_y(t)) + F_z(t),$$

$$\phi(\gamma) = \begin{cases} \gamma / 0,05 & \text{if } \gamma \geq 0 \\ -\gamma / 0,1 & \text{if } \gamma < 0 \end{cases}$$

- $F_z^{ref}(t)$  is the actual lumbar compressive force of the test apparatus in z-axis direction during the reference movements (without robot);
- $F_z(t)$  is the actual lumbar compressive force of the test apparatus in z-axis direction during the reference movements (with robot);
- $M_y^{ref}(t)$  is the actual lumbar bending moment of the test apparatus around y-axis during the reference movements (without robot);
- $M_y(t)$  is the actual lumbar bending moment of the test apparatus around y-axis during the reference movements (with robot).

The axes of the coordinate system are shown in [Figure 1](#).

NOTE 1 In general, assistive torque of a robot interferes the duration of the movement and the compressive force on the lumbar disks of the user. This is a source of instability of the test results. Therefore, this document adopts a time average within a specific time range during the reference movements.

NOTE 2 A human would stiffen his/her muscles to resist the change of posture by the lumbar bending moment around the y-axis. This tension of the muscles is known as a source of compressive force on lumbar disks. In contrast, the trunk of the test apparatus does not have muscles and its mechanical structure does not allow any change of posture. To compensate for this difference, the formula for LCR uses the corrected lumbar compressive force  $F(t)$  and  $F^{ref}(t)$  under the assumption that  $M_y(t)$  and  $M_y^{ref}(t)$  are all supported by virtual erector spinae muscles and virtual abdominal rectus muscles. This document adopts a 0,05 m moment arm from the L5/S1 lumbar disk to the virtual erector spinae muscles and a 0,1 m moment arm to the virtual abdominal rectus muscles<sup>[4][5]</sup>.

NOTE 3 During the reference movement, the weight of the upper body of the test apparatus is expected to always compress the fixed lumbar joint and  $\psi(\alpha, \beta) = \alpha - \beta$  always applies. However, this document defines  $\psi$  in a more general form to be applicable to tensile forces and to be consistent with the formula for ATI.

NOTE 4 When  $\psi$  is positive, the lumbar stress of the user is expected to be reduced during the reference movement. When  $\psi$  is negative, the lumbar stress of the user is expected to be increased during the reference movement.

**Table 1 — Time range to calculate ATI and LCR**

ATI <sup>b</sup>	LCR <sup>b</sup>	Reference movements	$t_1$ <sup>a</sup>	$t_2$ <sup>a</sup>
ATI <sub>1 000</sub> <sup>Lower</sup>	LCR <sub>1 000</sub> <sup>Lower</sup>	Lowering	$t_d - 1$ [s] <sup>c</sup>	$t_d$ [s] <sup>c</sup>
ATI <sub>200</sub> <sup>Lower</sup>	LCR <sub>200</sub> <sup>Lower</sup>	Lowering	$t_d - 0,2$ [s] <sup>c</sup>	$t_d$ [s] <sup>c</sup>
ATI <sub>1 000</sub> <sup>Hold</sup>	LCR <sub>1 000</sub> <sup>Hold</sup>	Holding	$\frac{t_d}{2} - 0,5$ [s]	$\frac{t_d}{2} + 0,5$ [s]

<sup>a</sup>  $t_1$  and  $t_2$  define a time range when the necessary torque of the user and the lumbar stress are the largest assuming the beginning time of each reference movement is 0 (see [Annex A](#)). Because the angle trajectories of the reference movement are increasing or decreasing monotonically, ATI and LCR can be considered as an average within a specific angle range. However, because 1) assistive torque can generate varying angle trajectories; 2) it is difficult to define the relevant angle ranges of the trunk, the hip joint and the knee joint simultaneously; and 3) the amount of data points for calculating the average can vary, this document adopts a time average to define ATI and LCR.

<sup>b</sup> ATI and LCR with a 1 s average (ATI<sub>1 000</sub><sup>Lower</sup>, ATI<sub>1 000</sub><sup>Hold</sup>, ATI<sub>1 000</sub><sup>Raise</sup>, LCR<sub>1 000</sub><sup>Lower</sup>, LCR<sub>1 000</sub><sup>Hold</sup> and LCR<sub>1 000</sub><sup>Raise</sup>) can also be considered as an indication whether the robot can output assistive torque and reduce the lumbar stress continuously. On the other hand, ATI and LCR with a 0,2 s average (ATI<sub>200</sub><sup>Lower</sup>, ATI<sub>200</sub><sup>Raise</sup>, LCR<sub>200</sub><sup>Lower</sup> and LCR<sub>200</sub><sup>Raise</sup>) can be an indication of how much the robot can reduce the peak of necessary torque and the compressive force on the lumbar disks responsively (see [Annex A](#)). This is due to the fact that they only focus on a short time range. This document adopts a 0,2 s response time for humans to reflect the reaction to sudden load on lumbar spinal cord<sup>[3][9]</sup>.

<sup>c</sup>  $t_d$  is the actual duration of the reference movement.

Table 1 (continued)

ATI <sup>b</sup>	LCR <sup>b</sup>	Reference movements	$t_1$ <sup>a</sup>	$t_2$ <sup>a</sup>
ATI <sub>1 000</sub> <sup>Raise</sup>	LCR <sub>1 000</sub> <sup>Raise</sup>	Raising	0 s	1 s
ATI <sub>200</sub> <sup>Raise</sup>	LCR <sub>200</sub> <sup>Raise</sup>	Raising	0 s	0,2 s

<sup>a</sup>  $t_1$  and  $t_2$  define a time range when the necessary torque of the user and the lumbar stress are the largest assuming the beginning time of each reference movement is 0 (see [Annex A](#)). Because the angle trajectories of the reference movement are increasing or decreasing monotonically, ATI and LCR can be considered as an average within a specific angle range. However, because 1) assistive torque can generate varying angle trajectories; 2) it is difficult to define the relevant angle ranges of the trunk, the hip joint and the knee joint simultaneously; and 3) the amount of data points for calculating the average can vary, this document adopts a time average to define ATI and LCR.

<sup>b</sup> ATI and LCR with a 1 s average (ATI<sub>1 000</sub><sup>Lower</sup>, ATI<sub>1 000</sub><sup>Hold</sup>, ATI<sub>1 000</sub><sup>Raise</sup>, LCR<sub>1 000</sub><sup>Lower</sup>, LCR<sub>1 000</sub><sup>Hold</sup> and LCR<sub>1 000</sub><sup>Raise</sup>) can also be considered as an indication whether the robot can output assistive torque and reduce the lumbar stress continuously. On the other hand, ATI and LCR with a 0,2 s average (ATI<sub>200</sub><sup>Lower</sup>, ATI<sub>200</sub><sup>Raise</sup>, LCR<sub>200</sub><sup>Lower</sup> and LCR<sub>200</sub><sup>Raise</sup>) can be an indication of how much the robot can reduce the peak of necessary torque and the compressive force on the lumbar disks responsively (see [Annex A](#)). This is due to the fact that they only focus on a short time range. This document adopts a 0,2 s response time for humans to reflect the reaction to sudden load on lumbar spinal cord<sup>[3][9]</sup>.

<sup>c</sup>  $t_d$  is the actual duration of the reference movement.

### 5.3 Test facility

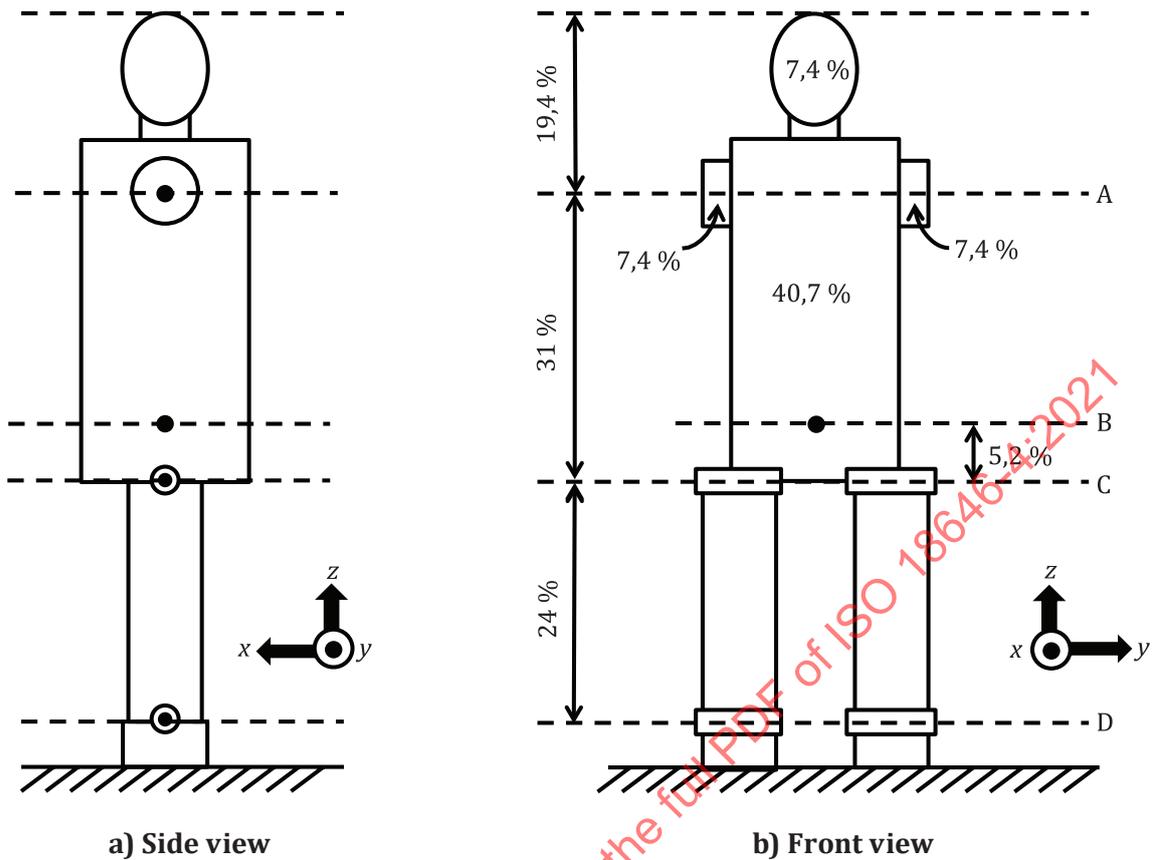
#### 5.3.1 Test apparatus

A test facility shall include a test apparatus which has a linked and actuated mechanism simulating a human user on which a robot is attached and tested. The robot is not included in the test facility. The ratios of its dimensions and the distribution of its mass shall comply with [Figure 1](#). In this figure, the height and mass of a representative user specified by the manufacturer are set as 100 %. The manufacturer may determine all other values not indicated in [Figure 1](#). If the manufacturer determines other values of ratio of height and mass are appropriate, they may be applied.

The compressive force to the lumbar z-axis and the bending moment around the lumbar y-axis are measured at the fixed lumbar joint as indicated in [Figure 1](#). The fixed lumbar joint is loaded with at least the weight of the upper parts of the test apparatus.

Only the hip joints and knee joints are active joints. If a test apparatus with arms and hands is used instead of a test apparatus with the substitutional weights at the shoulder joints, the arms of the test apparatus should be directed in a downward direction at any posture and each assembly of arm and hand should have 74 % of the mass of the representative user.

The density of each block of the test apparatus can be assumed to be constant.



- Key**
- A shoulder joint (fixed)
  - B lumbar joint (fixed)
  - C hip joint (active)
  - D knee joint (active)

NOTE 1 The ratio of dimension is indicated with an underline on a double-headed arrow. It is based on literature [2]; it indicates that the distance between a hip joint and L5/S1 spinal disk is approximately 83/1 610 (5,2 %) of the body height. Therefore, the fixed lumbar joint is located at the upper body part of the test apparatus. The data from Reference [2] were obtained by measuring a skeletal specimen of an adult European in the collection of the University of Tokyo (Specimen Number: P6). It is not an average of a specific population but used as a representative value.

NOTE 2 Assuming the arms and hands to be in a downward direction at any posture, the masses are concentrated to the shoulder joints.

NOTE 3 The distribution of mass is indicated in an area of body segment or by a single-headed arrow. This is from IEC 60601-1:2012, Figure A.19.

**Figure 1 — Dimension ratio and mass distribution of a test apparatus**

An example implementation of test apparatus is shown in [Annex D](#).

### 5.3.2 Reference movement and target trajectory

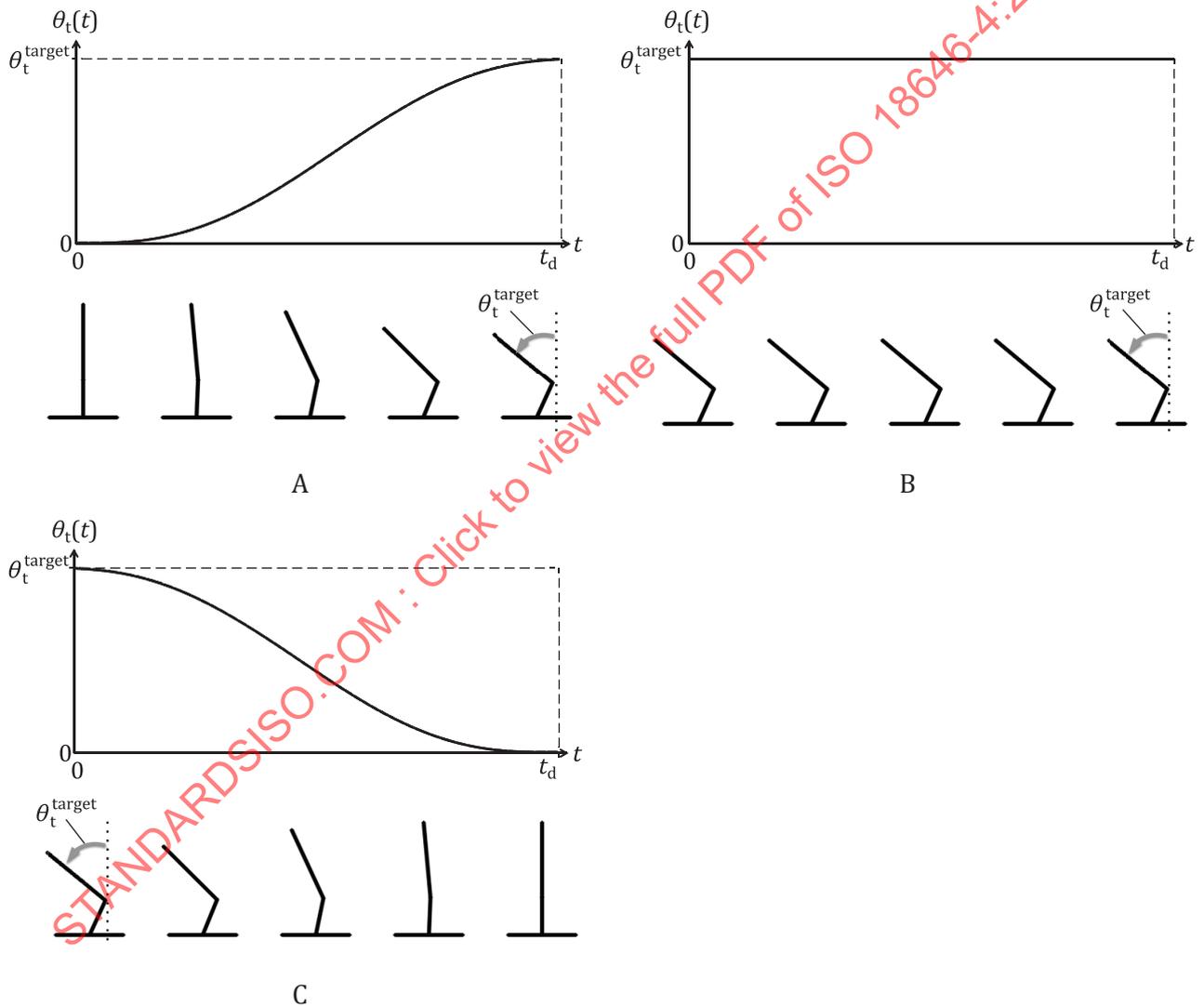
In this test, the test apparatus performs reference movements simulating lowering, holding and raising of the upper body. These reference movements are represented by a target trunk angle,  $\theta_t^{\text{target}}$ , the distribution ratio between the hip joint and the knee joint,  $k$ , and target duration,  $t_d$ , whose values shall be provided by the manufacturer.

The target trajectory of the trunk angle,  $\theta_t(t)$ , is given as the following quintic polynomial of time.

**Trunk angle** 
$$\theta_t(t) = \sum_{n=0}^5 a_n t^n, t = [0, t_d]$$

under  $t=0$  as the starting time of each reference movement, and  $\theta_t(t)=0$  at the upright position.

The set of  $a_n$  for each reference movement are determined to satisfy the initial angle  $\theta_t(0)$ , the final angle  $\theta_t(t_d)$  and the restraint condition where  $\dot{\theta}_t(0)=0, \dot{\theta}_t(t_d)=0, \ddot{\theta}_t(0)=0$  and  $\ddot{\theta}_t(t_d)=0$ . Ideally,  $\theta_t(0)=0$  and  $\theta_t(t_d)=\theta_t^{\text{target}}$  for lowering. Always  $\theta_t(t)=\theta_t^{\text{target}}$  for holding.  $\theta_t(0)=\theta_t^{\text{target}}$  and  $\theta_t(t_d)=0$  for raising. The target trajectories are illustrated in [Figure 2](#).



**Key**

- A target trajectory for lowering
- B target trajectory for holding
- C target trajectory for raising

**Figure 2 — Target trajectories for reference movements**

The hip joint angle,  $\theta_h(t)$ , and the knee joint angle,  $\theta_k(t)$ , are given as the following:

**Hip joint angle**  $\theta_h(t) = k\theta_t(t)$

**Knee joint angle**  $\theta_k(t) = (1-k)\theta_t(t)$

NOTE 1 These formulae use the relationship that  $\theta_t(t) = \theta_h(t) + \theta_k(t)$ .

NOTE 2 The trunk angle  $\theta_t(t)$  is defined as a quintic polynomial of time because the trajectories of each angle when humans lower, hold and raise a load are almost consistent with a quintic polynomial of time.

NOTE 3 If  $\theta_t^{\text{target}}$  is  $50^\circ$  as shown in Table 2,  $k$  can be 1,5 because  $k$  actually obtained from the measurement of humans' movement varies from 1,3 to 1,7 depending on each individual and the weight of each load.  $t_d$  can be 2 s.

NOTE 4 Generally, keeping a small angle at the trunk joint is preferred for reducing the lumbar stress during lowering, holding and raising. In this case,  $k$  can be more than 1,5 and  $t_d$  for lowering and raising can be shorter than 2 s. For example, if  $\theta_t^{\text{target}}$  is  $25^\circ$ ,  $k$  actually obtained from measurement of humans' movement is approximately 3,0 and  $t_d$  for lowering and raising is 1,5 s.

Table 2 shows an example of reference movements.

**Table 2 — Example of reference movements ( $\theta_t^{\text{target}} = 50^\circ$ ,  $k = 1,5$  and  $t_d = 2$  s)**

Reference movements	Trunk angles $\theta_t(t)$ , <sup>a</sup>	Durations $t_d$
Lowering	$0^\circ$ to $50^\circ$	2 s
Holding	$50^\circ$	2 s
Raising	$50^\circ$ to $0^\circ$	2 s

<sup>a</sup> Generally, the posture of the trunk as large as  $50^\circ$  is undesirable because the stress on lumbar disks gets so large. However, it can occur when the user raises a load from the ground or lifts another person. Therefore, a  $50^\circ$  posture of the trunk is a situation where a user needs the assistive torque of the robot. This is the reason why it should be evaluated, at  $50^\circ$ , how much assistance the user receives from the robot to the user and how much reduction the robot effects on the compressive force at the lumbar disks.

A controller for the test apparatus shall control its trajectories during the reference movements within an error of  $\pm 5^\circ$ , with and without a robot. The actual duration of each reference movement can differ from the target duration  $t_d$  for lowering and raising.

For a robot with biological input, the actual torque of hip joints of the test apparatus should be fed to the robot as input in place of the input from the user.

For a robot with kinematic input, no extra connection is needed between the robot and the test facility.

For a robot with command input, its control operation is done in accordance with a user manual during the reference movements and/or an interval between them.

If a low pass filter is used to process the data from the test apparatus to calculate ATI and LCR, its cut-off frequency shall be at least 10 Hz.

**5.4 Test procedure**

- a) Reference movements, the parameters  $\theta_t^{\text{target}}$ ,  $k$  and  $t_d$  and, if needed, an additional load are specified by the manufacturer.

- b) The test apparatus performs three repetitions of the reference movements without a robot, in the following order: lowering, holding and raising.
- c) Attach the robot to the test apparatus in accordance with the user manual.
- d) Keep the test apparatus at the most upright position.
- e) Start the assistive operation of the robot in accordance with the user manual.
- f) The test apparatus performs three repetitions of the reference movements with the robot, in the following order: lowering, holding and raising.
- g) Stop the assistive operation of the robot in accordance with the user manual.
- h) Detach the robot from the test apparatus in accordance with the user manual.

## 5.5 Test result

The calculated ATIs and LCRs shall be declared in the test report along with the following parameters, which characterize the test apparatus and the reference movements used in the test.

- The height and the mass of a representative user applied for the test apparatus
- $\theta_t^{\text{target}}$ ,  $k$  and  $t_d$  applied to define the reference movements
- The sampling rate applied for the measurement

An example table of the test results is shown in [Annex C](#).

## 6 Test method for rate of assistance

### 6.1 Purpose

This clause describes the method of specifying and evaluating performance of lower-back support robots; this test measures the level of back support or assistance of a robot by comparing the hip joint torque of the dummy before and after wearing the robot.

### 6.2 Relevant characteristics

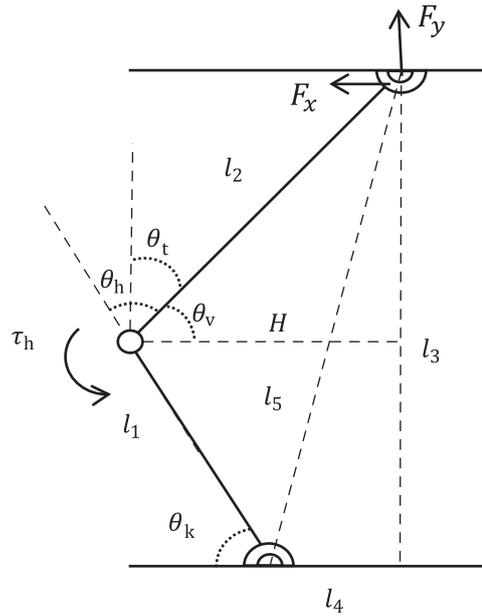
The amount of back support or assistance of a robot can be determined as the rate of assistance,  $R_a$ , as follows:

$$R_a [\%] = \frac{\int_{t_1}^{t_2} \tau_h^{\text{ref}}(t) dt - \int_{t_1}^{t_2} \tau_h(t) dt}{\int_{t_1}^{t_2} \tau_h^{\text{ref}}(t) dt} \times 100$$

where

- $\tau_h^{\text{ref}}$  is the reference hip torque measured during the specified motion without wearing robot;
- $\tau_h$  is the hip torque measured during the specified motion with the robot on;
- $t_1$  is the initial time of the specified motion;
- $t_2$  is the final time of the specified motion.

Hip joint torque  $\tau_h$  can be computed as follows using the generalized dummy geometry in [Figure 3](#).



- $l_5 = \sqrt{l_1^2 + l_2^2 - 2l_1l_2 \cos(\pi - \theta_h)}$
- $l_3 = \sqrt{l_5^2 - l_4^2}$
- $\theta_k = \pi - \left( \cos^{-1} \left( \frac{l_1^2 + l_5^2 - l_2^2}{2l_1l_5} \right) + \cos^{-1} \left( \frac{l_4^2 + l_5^2 - l_3^2}{2l_4l_5} \right) \right)$
- $\theta_v = \pi - \theta_h - \theta_k$
- $\tau_h = F_x l_2 \sin(\theta_v) + F_y l_2 \cos(\theta_v)$

Figure 3 — Dummy geometry for torque computation

### 6.3 Test facility

The test facility shall include a test apparatus which consists of a dummy to which a lower-back support robot can be attached as shown in Figures 4a) and 4b). The dummy is composed of a trunk and a thigh. The trunk and thigh should be covered with a composite material to emulate the human body form.

The mass distribution of a trunk is set to 55,5 % of the total mass of the representative user which is defined by the manufacturer according to Figure 1.

The position of the neck and the knee joint of the dummy can be changed manually along the slider so that it can implement several postures such as standing, waist bending (stoop pose), waist & knee bending (half squat), knee bending (squat) pose as shown in Figure 4c). Once the intended test posture is determined, the position of the neck and/or the knee joint can be fixed on the slider to maintain the intended posture.

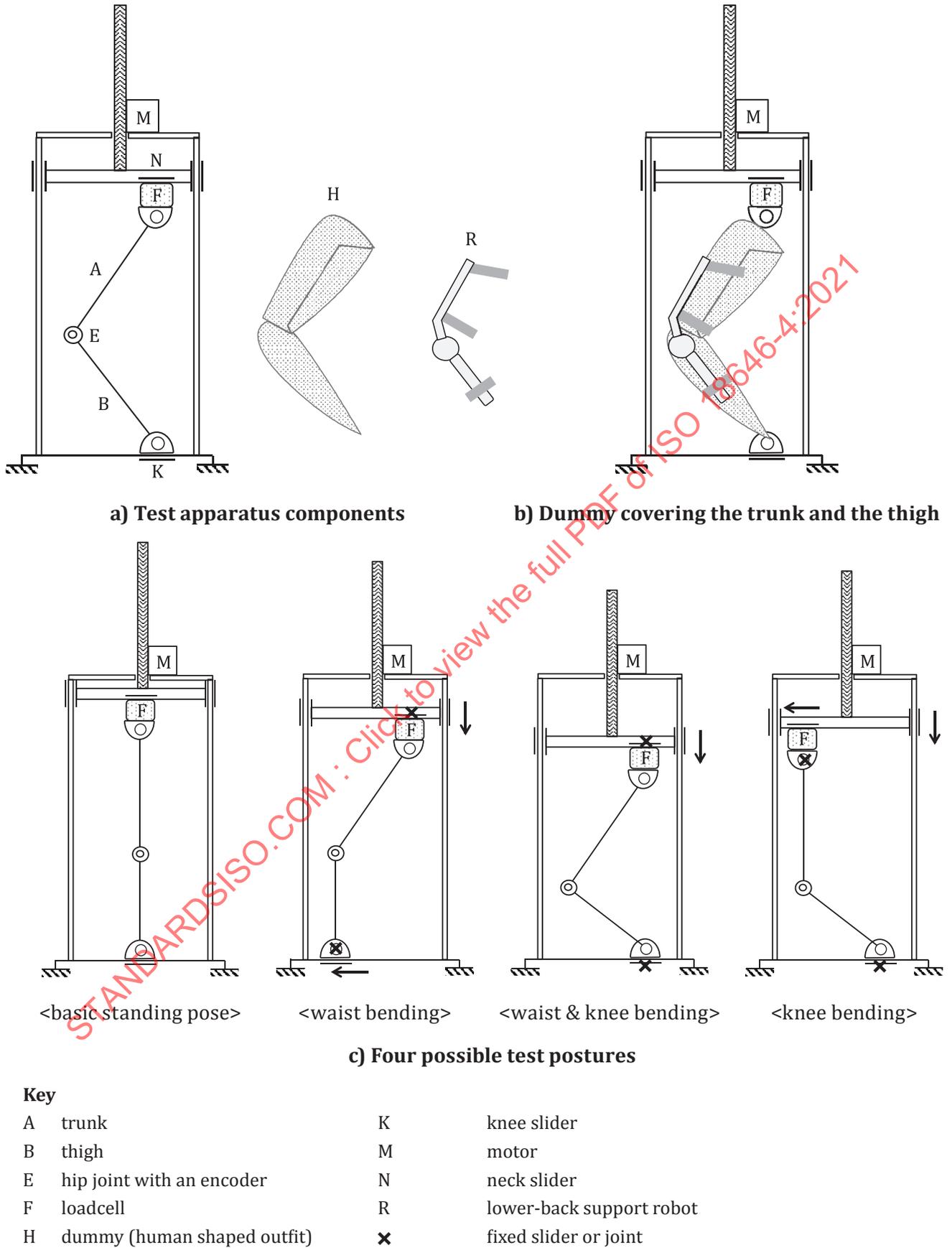
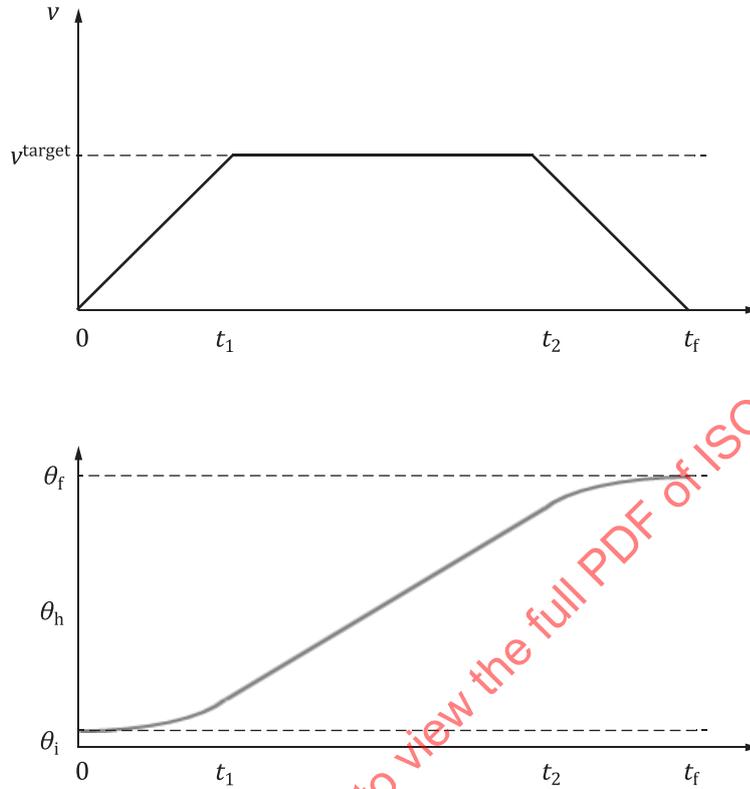


Figure 4 — Concept diagram of the test apparatus

The control plate or the head slider to which the head of a dummy is connected through a loadcell can move up and down along a ball screw by controlling the motor so that it can implement the above mentioned four motions in [Figure 4](#). The velocity profile of the control plate to implement the specific test posture (motion) can be determined by the manufacturer or by the reference movements in [5.3.2](#). [Figure 5](#) is a sample velocity profile used for lowering the trunk in half squat pose.



$$v = \begin{cases} v^{\text{target}} \frac{t}{t_1}, & (0 \leq t < t_1) \\ v^{\text{target}}, & (t_1 \leq t < t_2) \\ v^{\text{target}} \frac{t_f - t}{t_f - t_2}, & (t_2 \leq t \leq t_f) \end{cases}$$

$$v^{\text{target}} = \frac{2(\theta_f - \theta_i)}{(t_f + t_2 - t_1)}$$

- Key**
- $\theta_i$  initial position
  - $\theta_f$  final position
  - $t_f$  final time
  - $\theta_h$  hip position (defined in [Figure 3](#))

**Figure 5 — Sample velocity profile used for lowering the trunk in half squat**

The loadcell installed between the neck joint and the neck joint slider measures the force in x and y direction when the dummy is lowering or raising up the trunk. At the hip joint, a rotary encoder is installed to measure the rotational angle of the hip joint.

An example implementation of test apparatus is shown in [Annex D](#).

## 6.4 Test procedure

- 1) Select the desired test motion among the following four poses.
  - a) Standing
  - b) Waist bending (stoop pose)
  - c) Waist & knee bending (half squat)
  - d) Knee bending (squat)
- 2) Fix the neck and/or knee joint position along the slider as shown in [Figure 6](#), [Figure 7](#) and [Figure 8](#) depending on the desired test motion. Note that “x” in these figures indicates the fixed joint and “-” is the passive sliding joint. Then set up the initial hip and knee bending angle by controlling the vertical position of the control plate according to the selected reference motion.

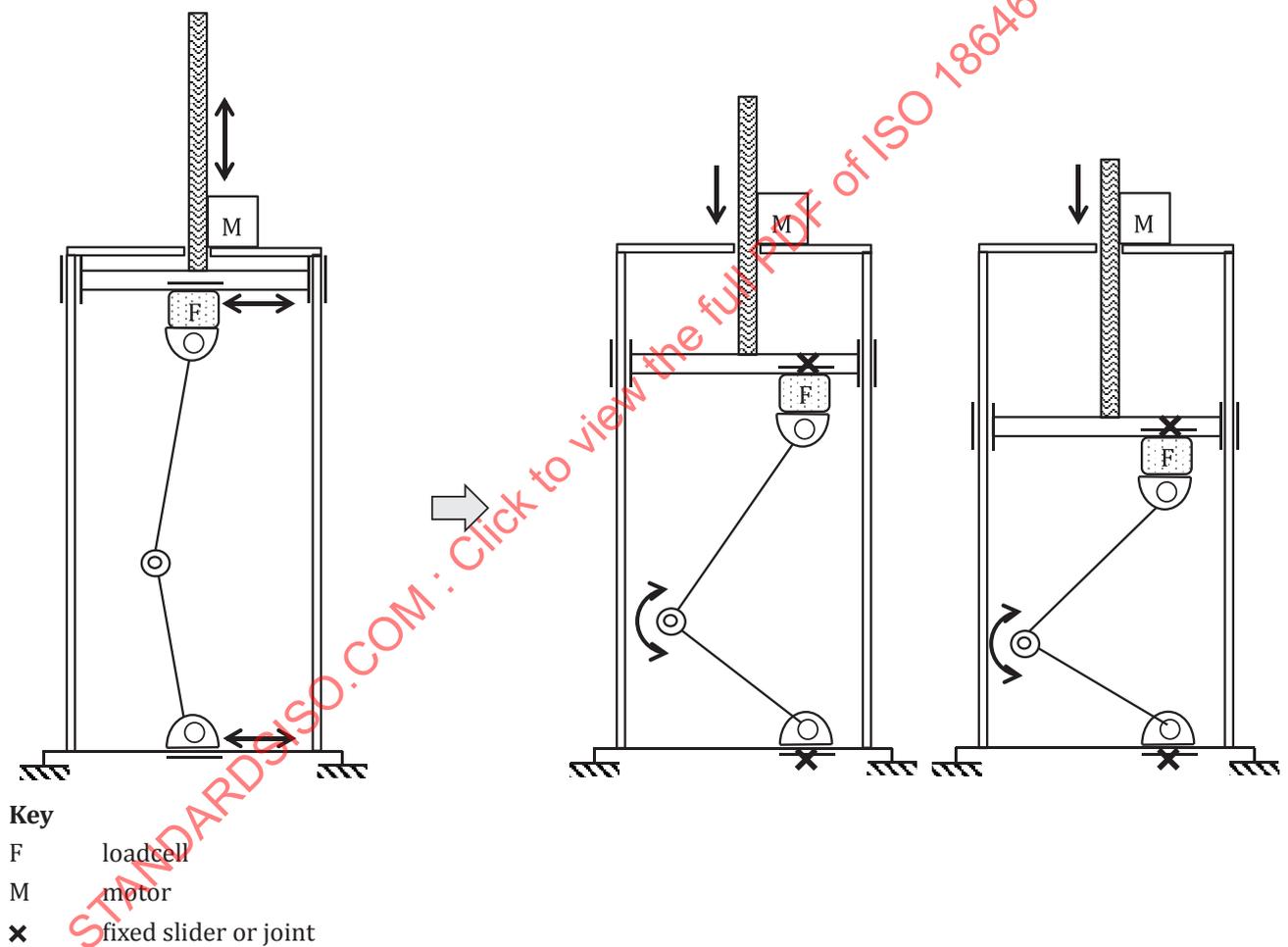
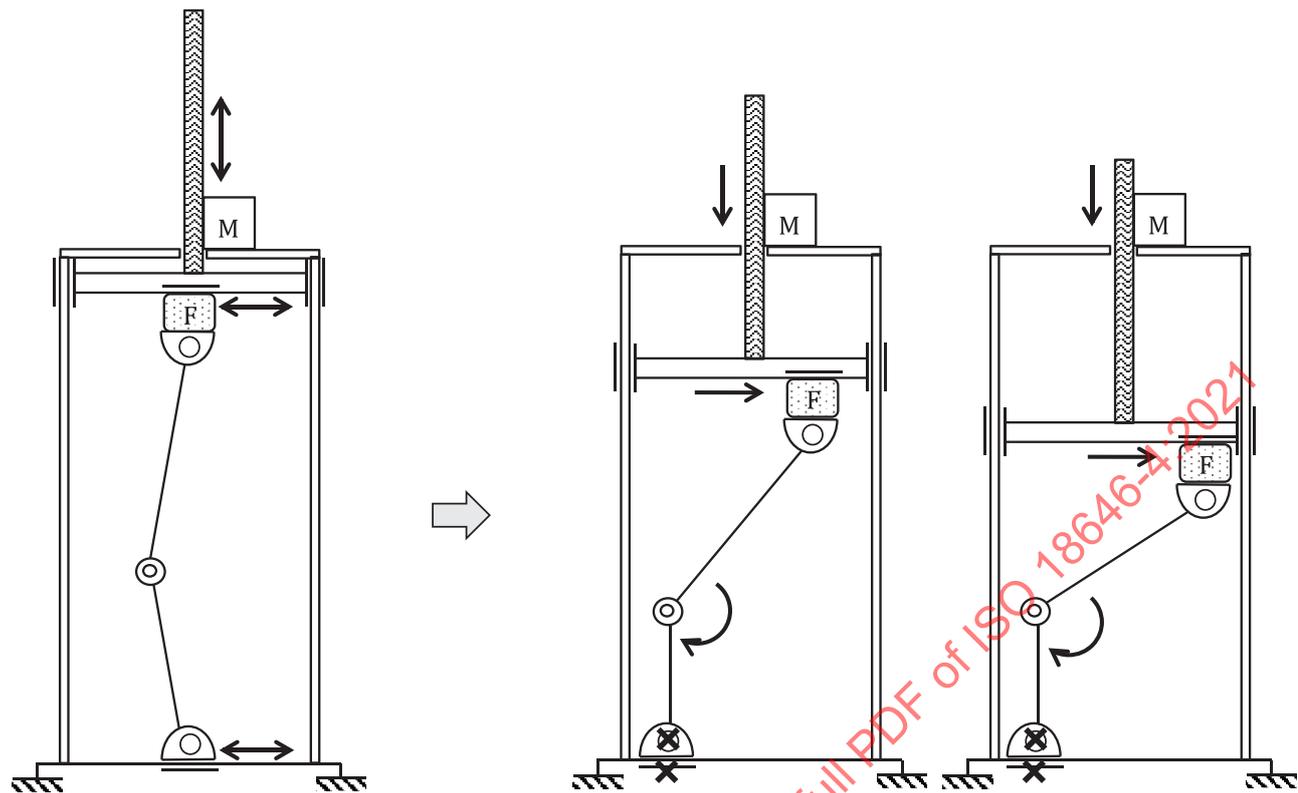


Figure 6 — Waist & knee bending



- Key**
- F loadcell
  - M motor
  - × fixed slider or joint

Figure 7— Waist bending



- iv) stand up by unbending the hip joint for two seconds;
- v) stand upright (final pose).
- c) Knee bending (squat pose):
  - i) stand upright (initial pose);
  - ii) sit by bending the knee joint for two seconds;
  - iii) maintain the sitting pose for two seconds;
  - iv) stand up by unbending the knee joint for two seconds;
  - v) stand upright (final pose).
- 5) Compute the torque at the hip joint during the reference motion using the formulae in [Figure 3](#) and record it as the reference torque  $\tau_h^{\text{ref}}$ .
- 6) Attach the robot to the dummy and repeat the step 4) and record the computed torque as  $\tau_h$ .
- 7) Detach the robot from the dummy.
- 8) Compute the rate of assistance using (1)
- 9) Repeat steps 4) to 8) three times
- 10) Compute the average of the rate of assistance

### 6.5 Test result

The average rate of assistance shall be declared in the test report along with all parameters characterizing the dummy, and the reference motion used in the test.

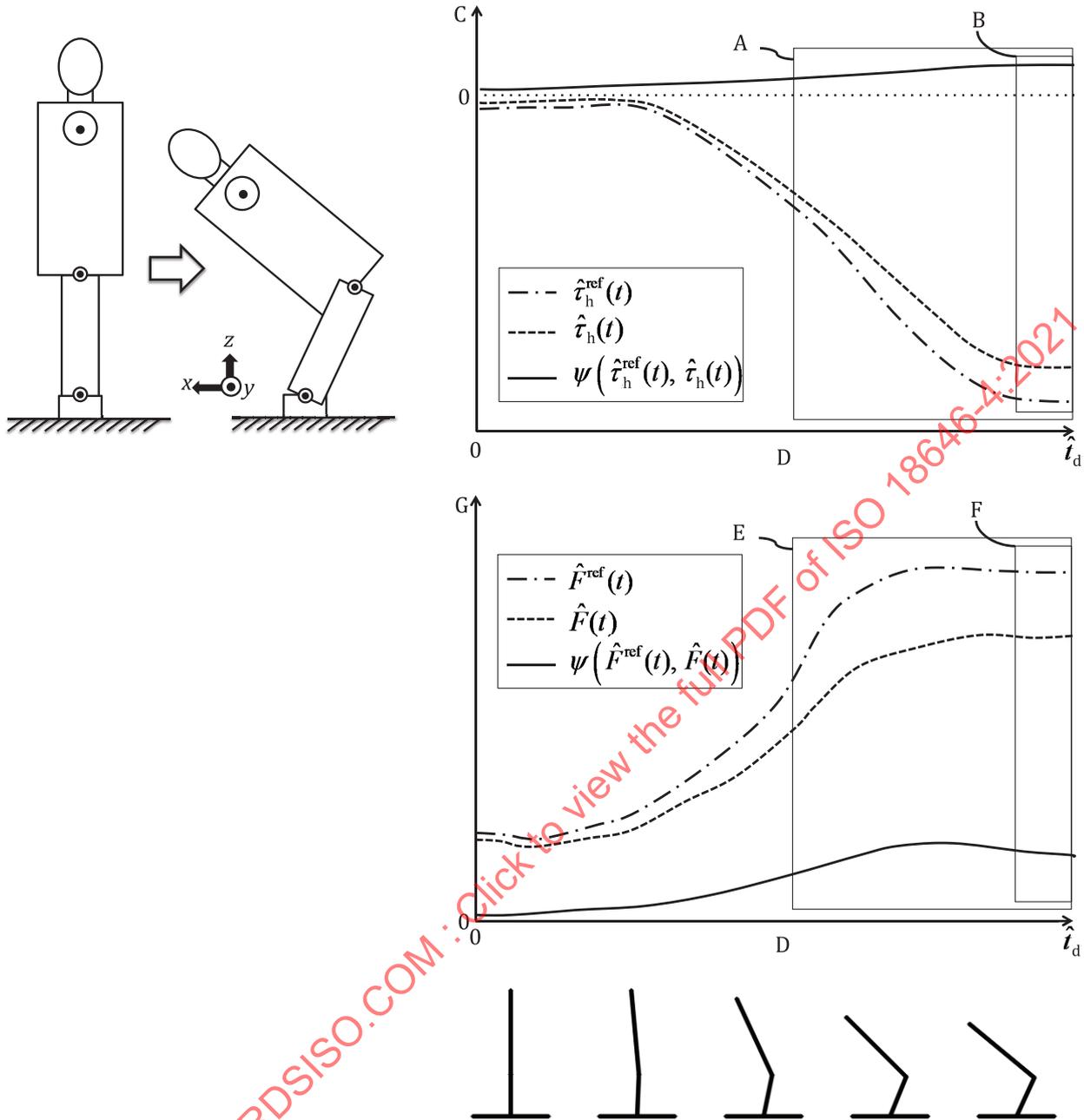
## Annex A (informative)

### Time range of ATI and LCR

[Subclause 5.2](#) uses the time ranges of [Table 1](#) to calculate the ATIs and the LCRs. This annex gives a better understanding of the ATIs and the LCRs by exemplifying data during the reference movements and the time ranges of the ATIs and the LCRs

[Figure A.1](#), [Figure A.2](#) and [Figure A.3](#) indicate examples of data obtained when the test apparatus performs the reference movements: lowering, holding and raising of the upper body, respectively, and  $\psi$  to be used to calculate the ATIs and the LCRs in [5.2.2](#) and [5.2.3](#).

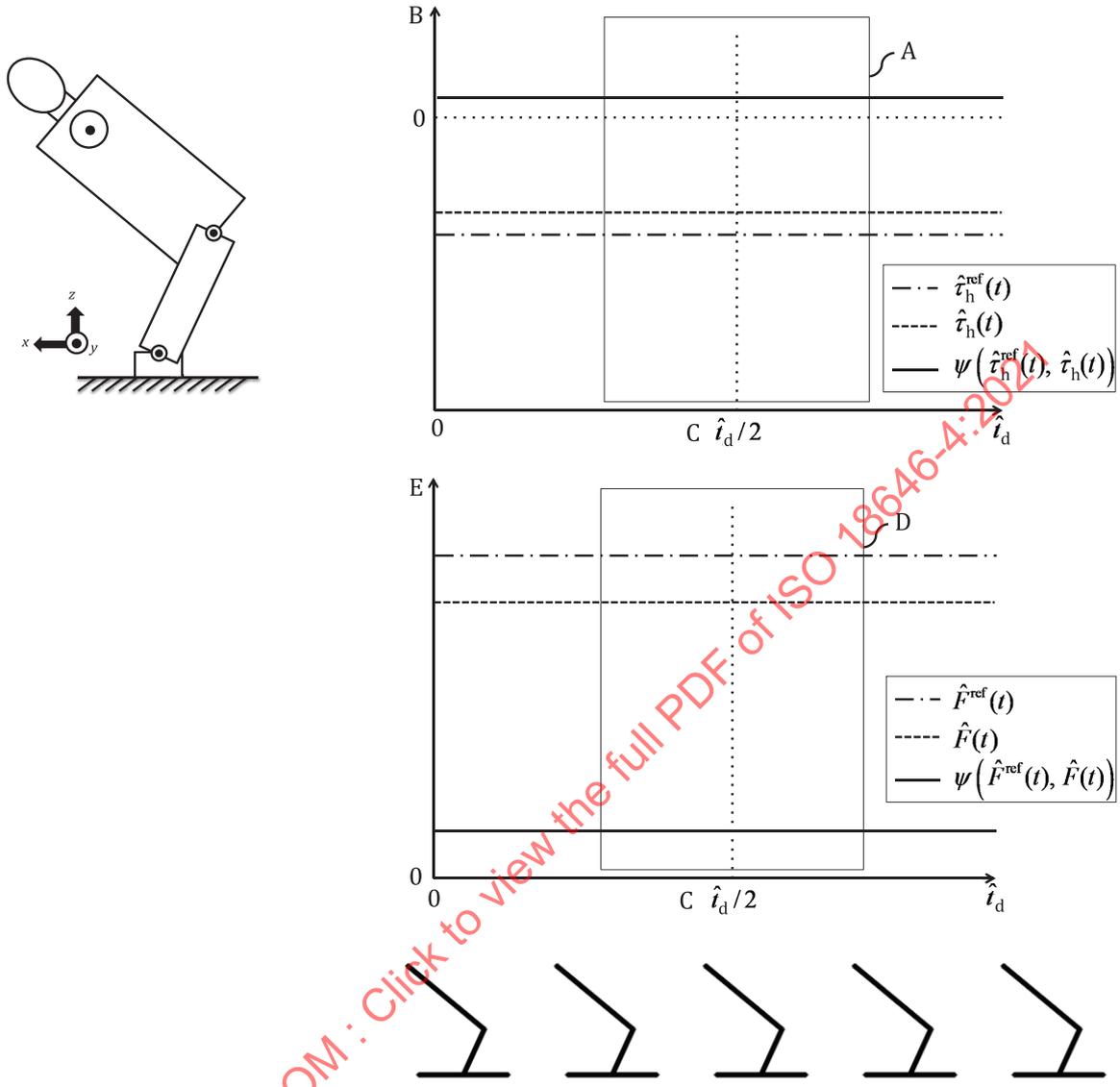
As shown in [Figure A.1](#), [Figure A.2](#) and [Figure A.3](#), ATI and LCR with a 1 s average ( $ATI_{1\,000}^{Lower}$ ,  $ATI_{1\,000}^{Hold}$ ,  $ATI_{1\,000}^{Raise}$ ,  $LCR_{1\,000}^{Lower}$ ,  $LCR_{1\,000}^{Hold}$  and  $LCR_{1\,000}^{Raise}$ ) can also be considered as an indication whether the robot can output assistive torque and reduce the lumbar stress continuously. On the other hand, ATI and LCR with a 0,2 s average ( $ATI_{200}^{Lower}$ ,  $ATI_{200}^{Raise}$ ,  $LCR_{200}^{Lower}$  and  $LCR_{200}^{Raise}$ ) can be an indication of how good a response the robot can show to reduce the peak of necessary torque and the compressive force on the lumbar disks.  $ATI_{200}^{Lower}$  and  $LCR_{200}^{Lower}$  for the lowering movement can also be considered as an indication of whether the robot can output assistive torque and reduce the lumbar stress until finishing the movement.  $ATI_{200}^{Raise}$  and  $LCR_{200}^{Raise}$  for the raising movement can also be considered as an indication of whether the robot can output assistive torque and reduce the lumbar stress at the beginning of the movement.



**Key**

- A time window for  $ATI_{1000}^{Lower}$
- B time window for  $ATI_{200}^{Lower}$
- C torque [Nm]
- D time [s]
- E time window for  $LCR_{1000}^{Lower}$
- F time window for  $LCR_{200}^{Lower}$
- G force [N]

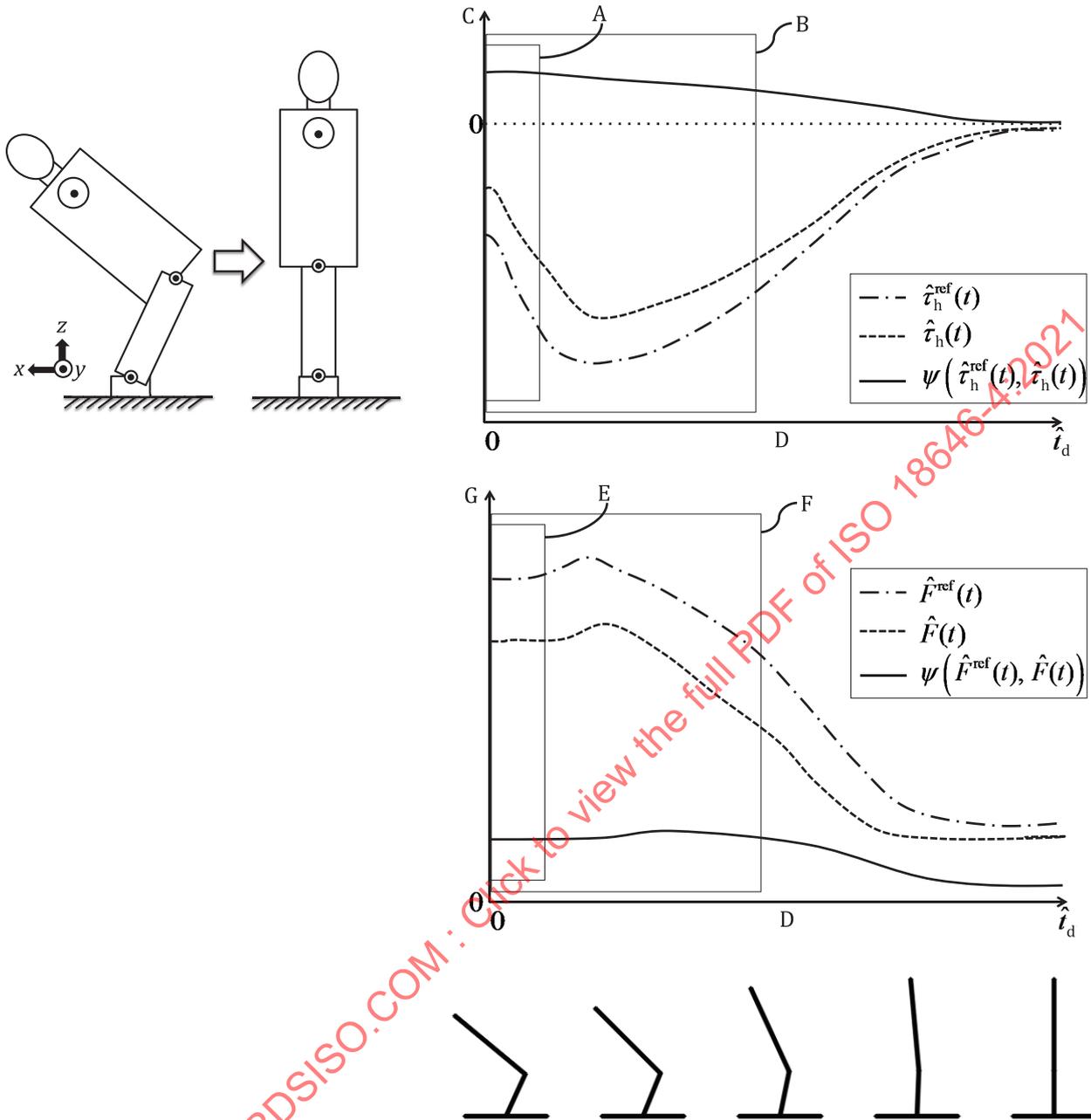
**Figure A.1 — Example of data during the lowering movement and time range of ATI and LCR**



**Key**

- A time window for  $ATI_{1\,000}^{Hold}$
- B torque [Nm]
- C time [s]
- D time window for  $LCR_{1\,000}^{Hold}$
- E force [N]

**Figure A.2 — Example of data during the holding movement and time range of ATI and LCR**



**Key**

- A time window for  $ATI_{200}^{Raise}$
- B time window for  $ATI_{1\,000}^{Raise}$
- C torque [Nm]
- D time [s]
- E time window for  $LCR_{200}^{Raise}$
- F time window for  $LCR_{1\,000}^{Raise}$
- G force [N]

**Figure A.3 — Example of data during the raising movement and time range of ATI and LCR**