3D Reference-Based Skeletal Movement Evaluation

Lars Lehmann[a], Roman Seidel[b] and Gangolf Hirtz[c]
Digital Signal Processing and Circuit Technology, Chemnitz University, Reichenhainer Str. 70, Chemnitz, Germany

Keywords: Segment Reference, Visualisation, Feedback Control, Assisted Motion Control, Motion Error Detection, 3D Realtime Animation.

Abstract: In a medical therapy, the exact execution of the training exercises developed by the therapist is a crucial task for the success of the therapy. Currently, a therapist has to treat up to 15 patients at the same time on an outpatient basis. To compensate this deficit, an automated assistance system needs to be created. Previous approaches have focused on a parameterised segment angle-based assessment for training exercise feedback. This work focuses on a reference-based approach. This reference is created by the therapist and thus corresponds to the ideal movement model and can be individually adapted to the patient. It is necessary to compare this reference with the patients' real movement in real time, to detect deviations and to output them as errors. For this purpose, the reference can be adapted to the body size of the patient and the patients' current position and orientation can be taken into account, or it can be described by reference segments, i.e. an angle-based comparison of the reference. Our work highlights the the segment and reference-based assessment approach and compares them to each other.

1 INTRODUCTION

After a hip operation, the persons treated must complete a rehabilitation phase of several weeks in a special stationary therapy centre. During the therapy, one therapist looks after up to 15 patients (Nitzsche, 2018). It is not possible for the therapist to carry out the therapy in the required quality because they lack the necessary overview. This lack of specialist control leads to errors in the execution of the patients' movement. These systematic incorrect movements due to unavailable control aggravate their hip problems and delay or even prevent recovery (Lösch, 2019).

Demographic change will increase the number of patients and decrease the number of therapists (Budliger, 2021). In order to prevent a collapse of therapeutic medicine, computer-supported assistance in the implementation of therapy is indispensable. Therefore, a prototype was developed, which uses a depth sensor to realise a skeletal extraction and detects and evaluates the patients' movements directly at runtime. The markerless assistance system works in real time and supports the therapists in this way. For visualisation, the assistance system uses a three-dimensional avatar, modelled on a human body, to represent a patient and to detect and map his movements. The avatar is formed by a three-dimensional mesh model whose surface is described by triangles and is connected to the extracted skeleton so that the patients' movements directly affect the model. The mesh model is divided into segments according to the coupled skeleton, which are used for direct visualisation(Lehmann, 2020). If an error is detected during the movement, the corresponding segment involved in the error is coloured directly on the mesh model(Wolff, 2018). Figure 1 shows an error and the colouring of the involved segments with the help of known traffic light colours.

Figure 1: Representation of direct error mapping.

When coloured red, this extraction segment is directly involved in the error. Yellow stands for a warning, the

[a] https://orcid.org/0000-0001-9778-8479
[b] https://orcid.org/0000-0002-3144-1488
[c] https://orcid.org/0000-0002-4393-5354

Lehmann, L., Seidel, R. and Hirtz, G.
3D Reference-Based Skeletal Movement Evaluation.
DOI: 10.5220/0011969200003497
In *Proceedings of the 3rd International Conference on Image Processing and Vision Engineering (IMPROVE 2023)*, pages 150-155
ISBN: 978-989-758-642-2; ISSN: 2795-4943

segment is in a critical movement area. If the segment is coloured green or according to the mapped texture (Capizzi, 2002), no error has been detected and the movement is correct.

An angle-based comparison of the skeleton's bone joints for motion immobilisation is relatively easy to realise, but it also has some disadvantages. Creating the comparative movements is quite time-consuming, as each individual aspect of the movement must be specified and agreed separately. It would be simpler to have a movement recording that can be generated quickly and used for comparison with the current movement. These recorded references are individualised ideal movements generated by the therapist. Two of these reference implementations are presented and compared in this paper.

2 STANDARD SEGMENT-BASED METHOD

The general segment-based movement assessment (SBE) concentrates on the observation of the skeleton points and their position in relation to each other. The individual points of the extraction skeleton are known and also their connection to each other. These are used to read angles between segments and match them. In this way it can be determined whether a movement within a predefined frame or is ending outside of it(Zhao et al., 2014). This method is a standard method for a motion assessment(Röder et al., 2023)(Ren et al., 2005).

At the beginning of the movement evaluation, it is necessary to define the individual 3D movements and their corresponding error patterns(Antón D, 2015). The movement definitions are needed to realise the repetition counts. The error patterns help to determine deviations in the intended movement and to give hints for the real execution of the movement. In the assistance system, various SBE scenarios have been created. There are abduction, flexion and extension movements for both the lower and upper extremities that can be detected and evaluated. In this section an example creation of the right leg abduction and its error patterns are shown.
Abduction is defined by the movement of a body part away from the body axis (Menche, 2003). In the figure 2 the whole skeleton is shown during an abduction of the right leg. The movement is visualised mirror-inverted because the sensor extraction is done in this way.

The joint points A, B, C and D necessary for calculating the abduction angle are marked in green. The angle results from observing the position of two intersection lines. The intersection line results from two joint points belonging to each bone. The actual angle α is obtained by substituting the intersection lines into equation 1.

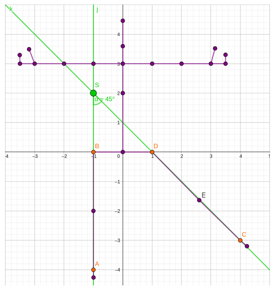

Figure 2: 2D representation of an abduction of the right leg. The angle α between the two through the straight lines AB and CD is determined and used as a motion measurement.

$$cos(\alpha) = \frac{u \cdot v}{|u| \cdot |v|} \quad (1)$$

The angle α is the desired goal of this movement where $u = S - A$ and $v = S - C$. This angle must be achieved during the real-time movement in order to realise a correct repetition of the movement.

Additional parameters for the movement guidance must be checked in order to achieve an optimal training result. For example, it must be ensured that the movement takes place primarily in the xy-plane if the patient is standing frontally in front of the extraction sensor. This plane should not be left during the abduction movement. In addition, the knee, i.e. the angle between the vectors CE and DE, can be bent too much during the movement. This simplified movement results in a compensatory movement that is contrary to recovery. A bent upper body, i.e. a tilting of the entire upper area of the extraction points, also has an unfavourable effect on the target movement. Only when all these factors are taken into account can a successful movement be counted and processed as a repetition. Otherwise, the additional parameters create an error image that is immediately presented to the patient visually in order to correct his or her movement execution during the next repetition.

If this SBE-based movement is to be changed or even extended, application-related problems arise. If the angle of the abduction is changed, the associated variable must be changed either directly in the source code or with the help of a GUI connection, which is still quite easy to do with this simple abduction movement. Although in this case the user has to switch through the four parameter defaults and parameterise the appropriate one, this can be done. If, however, in addition to this abduction, a flexion of the left arm and a slightly offset extension of the right arm with a pendulum movement of the upper body are to be realised, a GUI-based arrangement of the training movement quickly reaches its limits, becomes extremely time-consuming to handle and results in confusing layouts. Temporally different movement sequences are difficult to implement with the SBE.

3 REFERENCE-BASED METHODS

In order to avoid the time-consuming manual individual parameterisation of an SBE training, reference-based methods of training planning can be used. The creation and use of the individualized patient reference is carried out by the therapists with the assistance system (Lehmann et al., 2021). In the assistance system's reference recording mode, the therapist's movements are recorded and stored as a sequence in the system. These movement sequences are available as digitized 3D skeletal movements. A reference is equivalent to a repetitive motion where the start and end points can be identified. The advantage of the reference is that it can be created by an experienced therapist, making it an ideal therapy and individually adapted to the patient.

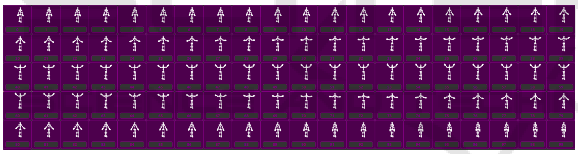

Figure 3: A short movement reference that shows the raising and lowering of both arms.

The figure 3 shows a reference image, where the reference consists of 100 individual steps and serves as the basis for the patients' assisted movement rehabilitation. The movement in the first position of the reference and the last one are similar in their orientation and position.

The original skeleton extraction does not determine the exact and real extraction points in every frame due to varying lighting conditions, sensor deficits and model extraction inaccuracies. As a result, when motion vectors of the individual frames are recorded, shifts and deviating, geometrically jumping points occur. This has to be smoothed in order to design the subsequent processing of the reference in the best possible way and to reduce input errors as much as possible.
The comparison of a current movement with a movement reference is explained using two methods integrated in the assistance system.

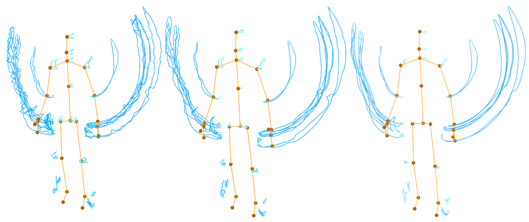

Figure 4: The original reference on the left is imprecise due to errors in the extraction of the individual points and requires smoothing. The mean reference in the middle was smoothed with the SMA(Dreszer, 1975) and ten neighboring points in each direction of the gradient. The right reference was smoothed ten times consecutively, involving two adjacent points.

3.1 Reference Based Evaluation (RBE)

Therapists and patients differ in their physical size. The reference created by medical professionals is therefore not immediately applicable to the anatomically deviating patients. An adjustment of the sizes of skeletal extractions must be made beforehand. The current skeletal information of the patient is used for the 3D visualisation of the avatar. Since the current extraction points are used for the visualisation, the size must be adapted to the reference (figure 5).

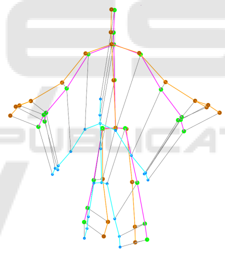

Figure 5: The original reference (blue) has been adjusted to the bone length of the current real sequence (orange). The adapted reference (magenta) is the target of the adjustment.

For the comparison of the movements between the reference and the current skeleton some calculations and parameter declarations are needed. Blue sections in figure 6 are reference sections, orange stands for the current movement and the sections in the orange box are calculated at runtime.
At the beginning, the length of the patient's bones must be determined in order to use this for the adjustment of the reference skeleton. For this purpose, the assistant system tells the patient to stand relaxed and calmly frontally in front of the extraction sensor in order to keep his bone length extractions as stable as possible. The initialisation process must provide at least 60 frames of almost identical length values in order to use these as the basis for the adaptation. These bone lengths are applied to the smoothed reference and this is adapted once to the corresponding size.

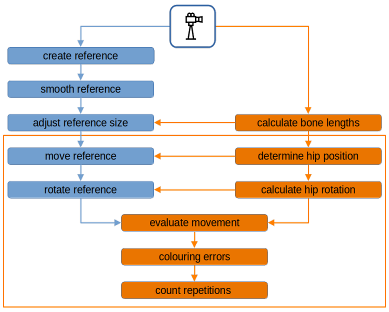

Figure 6: The stages of RBE based movement assessment to be carried out.

The scaled reference S must be adjusted to the patients' position. For this, the difference vector v, which is defined between the root node of the reference skeleton S_r and the root node of the patient skeleton P_r is calculated. The root vector of the skeleton is the vector from which all extraction points of the skeleton originate and is usually equated with the middle hip.This difference vector v shows the location difference between reference S and the current extraction P and comes about when the standing positions of the patient and the reference are not exactly on top of each other. To compensate for this, every extraction point and every sequence of the scaled reference S is now subtracted with this displacement vector v.

Another adjustment to be made for each extraction run is the rotational shift of the current motion skeleton to the associated reference frame. This difference can arise when there is a deviation in the orientation rotation of the reference to the current motion. The rotation of the entire skeleton can best be understood at the hip, because this is anatomically fixed. It is therefore not possible to move the left and right hip extraction point independently of each other, since these two are connected by the hip bone(Schwegler and Lucius, 2016).

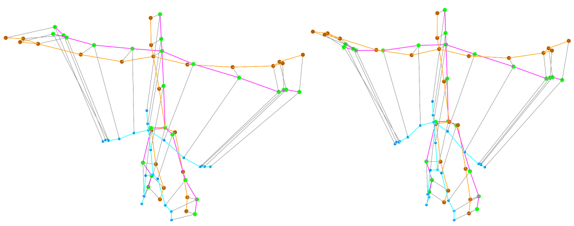

Figure 7: When comparing a non-rotated (left) and rotated hip (right), the larger distance between the skeletal points is noticeable in the former.

The problem of the resulting angle between the hip vectors to be compared is shown in figure 7. In both cases the reference has been adjusted to the current movement. The comparison was made on an identical frame index of the animation. Hip rotation was ignored in the left figure. The distances between the extraction points of the blue reference and the magenta adaptation skeleton are much larger than on the rotated side.

After the size, the position and the rotation difference have been applied to the reference S, the comparison of the extraction vectors can be generated. For this, all adapted reference sequences R_j are compared with the current extraction points P. Since the movement executions are not completely identical, a 3D vector Δ is used to calculate the valid tolerance range for the current extraction point comparison.

$$\sum_{j=0}^{k}\sum_{m=0}^{n}(S[j]_m-\Delta) < P_m < \sum_{j=0}^{k}\sum_{m=0}^{n}(S[j]_m+\Delta) \quad (2)$$

The above inequality 2 is checked for each dimension. If one of the three-dimensional extraction points is outside of this tolerance range, it is detected as a motion error and is colored.

3.2 Segment Reference Based Evaluation (SRBE)

The RBE considered in the previous section is a relatively complex procedure to carry out the desired movement evaluation. To overcome this complex preparatory steps such as stable bone length calculation and its adapted reference adjustment as well as hip transformation adjustments per updated extraction frame must be carried out. These disadvantages can be avoided with SRBE.

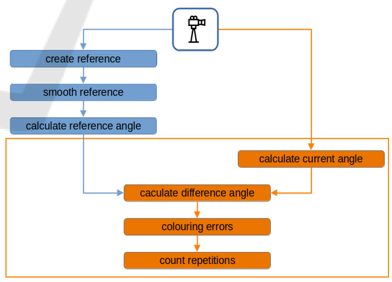

Figure 8: The stages of SRBE based movement assessment to be carried out.

Blue sections in figure 8 are reference sections, orange stands for the current movement, the sections in the orange box are calculated at runtime. The angles between the bones are independent from the length of the bones. Starting from a root extraction point, which is found in the middle hip extraction point, the known bone connections of neighboring extractions and their connection angles can be used to determine the position of the extraction points under consideration. In contrast to the reference-based comparison, the one-off calculation of the bone lengths is saved, as is the adjustment of the reference skeleton sizes, the permanent shift of the reference to the origin and the rotation of the hip, since the angular considerations of the skeletal extraction points already include them.

The calculation of the angles between the individual bone segments of the reference must also be carried out once, at the beginning of the movement tracking. The already smoothed reference animation is required for this. The calculation of the individual angles is done segment by segment for each recorded movement sequence by iterating step by step over the total number of reference movement images. To do this, it is necessary to know how the skeletal extraction points are assigned to the segments, i.e. which bones are connected to each other. Then the required angles between these joined bones can be calculated. The connected bone segments of the skeleton are taken as straight lines and each is transferred into the parametric form. It is known that these straight lines intersect in space as they converge at the associated extraction point. The equation of a straight line is as follows.

$$x = a + \lambda u \tag{3}$$

The vector a is the extraction point of a bone from the bone segments table that corresponds to the first index. The parameter u is the direction vector of this bone line. That is the difference between the end vector b of the straight line and its start vector a. Each value of λ corresponds to exactly one point on the straight line. The associated indices of the bones can be read from the given composite bone segment table of the skeleton extraction.

Once the parametric forms have been determined for both lines that belong together, the angle between the two can then be calculated. For this, the direction vector u of the first bone in the segment is processed with the direction vector v of the second bone in the formula 1.

The arccosine of the angle α returns a value between 0° and 180°. These angles are recorded for all segments of the frame and across all frames of the animation and saved in the assistance system as a variable *rsa* for later processing. After the angles have been determined for all segments of the reference frame and across all possible frames of the recorded animation, they can now be used for a movement comparison with the current angle segments.
However, it is not enough just to determine the angle of the bone segment. The position of the composite bones in relation to the connection vector S must also be evaluated. For this, the position of the points A and B must be evaluated. Therefore, the angles between

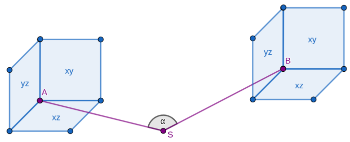

Figure 9: Calculation of the connection angle of the bone segment and the positional relationships of the composite bones.

AS and SB to the standard planes are calculated. By looking at the x, y and z values of the two points A and B and comparing them with the corresponding values of S, the direction of execution can be determined exactly. Positive or negative values are obtained, which are multiplied by the angles to the standard planes to determine the final direction angles. For each angle α there are three positive or negative angles for A and B.

The current angles are determined from the patient's current movement extraction. The calculation is analogous to the calculation of the reference angles, with the difference that the collection is not based on the total reference, but only on the current extraction. It is then checked whether a frame that meets the criteria is found in the set of reference segment angles R_α and the alignment angles of R_A and R_B of the entire reference animation. If a matching angular segment frame is available, the patient's current movement is judged to be correctly executed based on the segment angles P. Otherwise, a movement error is detected in the deviating extraction segment.

$$\sum_{j=0}^{k}\sum_{m=0}^{n}(R[j]_m - \Delta) < C_m < \sum_{j=0}^{k}\sum_{m=0}^{n}(R[j]_m + \Delta) \tag{4}$$

The deviation tolerances Δ of the current patient angle C_m are shown in the formula 4 and can be set in the system. The tolerance allow a controllable deviating movement execution with respect to the reference. This ensures that all patients, according to their fitness level, can perform these reference exercises. To increase the exercise intensity, only the tolerance has to be reduced to bring the patients more and more into the desired optimal starting reference during their exercises. For the comparisons of R_A and C_A and of R_B and C_B, there are similar tolerence frames. Only when all seven conditions are evaluated as correct is the executed patient movement also correct.

4 SUMMARY

The SBE is the standard method for performing the evaluation. Only the current angles between the defined and selected bone segments of the individual extraction frames are taken into account. If this angle corresponds to the previously created parameters and does not touch any of the necessary error patterns, the movement is evaluated as correct, otherwise it is marked as a non-compliant movement.

The RBE is a reference-based method and is therefore not parameterised like the SBE, but receives its comparison values from a previously created reference movement. This reference movement is created individually for the respective patient and serves as the basis for the targeted movement comparison.

With the RBE, the reference is adjusted to the size of the current patient and their specific spatial coordinates. During the execution of the patient movement, the patient is guided through the repetition with the help of bounding boxes that reflect the tolerance level of the movement deviation. If the patient moves outside the permissible range, an error is detected and a corresponding visual message is given to the patient.

The second reference-based method considered is the SRBE. This is not based on length comparisons but on the angles between the bone segments of the reference. These angles are also evaluated in terms of their orientation to determine the correct direction of execution of the given joint angle. Due to the angle evaluation, the SRBE is not limited to static length information and also works with changing reference skeletal sizes, for example when a patient moves towards or away from the extraction sensor.

Table 1: Advantages and disadvantages of the motion evaluation methods.

Description	SBE	RBE	SRBE
clearly error patterns	✓	(✗)	(✗)
fixed error patterns	✓	✗	✗
high creation time	✓	✗	✗
idealized reference	✗	✓	✓
speed evaluation	✗	✓	✓
fast execution speed	✓	(✓)	(✓)
single-joint overview	✗	✓	✗
real-time	✓	(✓)	✓
change position to cam	✓	✗	✓
easy GUI usage	✗	✓	✓

5 CONCLUSION AND FUTURE WORK

The generation and use of an individual reference has the advantage of subject-specific correct execution. A patient can then follow this reference to perform the best possible therapy. The two reference-based methods presented here can realise movement assessment. The RBE shows exactly those local 3D positions of the skeletal points that have to be approached by the patient, the SRBE enables this precise movement tracking on the basis of the evaluated angle sequences within the reference. The benefits of reference-based movement capture do not only extend to medical movement therapy. Rapid reference generation and reference evaluation could also be applied in other areas where skeleton-based motion detection would be helpful. The reference could be used for training steps in the assembly industry as well as for learning a musical instrument. As long as the movement patterns can be recorded and extracted, they can be evaluated for all movement-specific tasks and applied to the situation.

REFERENCES

Antón D, Goñi A, I. A. (2015). Exercise recognition for kinect-based telerehabilitation. In *Methods Inf Med. 2015*, pages 145–155.

Budliger, H. (2021). *Demografischer Wandel und Wirtschaft*. Springer Gabler, Berlin, 1st edition.

Capizzi, T. (2002). *Inspired 3D Modeling and Texture Mapping*. Cengage Learning PTR.

Dreszer, J. (1975). *Mathematik Handbuch*. Verlag Harri Deutsch.

Lehmann, L. (2020). Visigrapp 2020. In *Individual Avatar Skeletal based Animation Feedback for Assisted Motion Control*, pages 206–213. Scitepress.

Lehmann, L., Seidel, R., and Hirtz, G. (2021). Supervised skeleton-based reference movement adjustment. *Current Directions in Biomedical Engineering*, 7(2):1–4.

Lösch, C. (2019). Paper templates. In *Validation of an assistance system for motion analysis*. German Journal of Sports Medicine.

Menche, N. (2003). *Biologie Anatomie Physiologie*, volume 5. Urban und Fischer Verlag.

Nitzsche, N. (2018). *Assistierte Bewegungskontrolle in der Rehabilitation durch intelligente Sensortechnologie*. readbox unipress, Münster, 1st edition.

Ren, L., Patrick, A., Efros, A., Hodgins, J., and Rehg, J. (2005). A data-driven approach to quantifying natural human motion. *ACM Trans. Graph.*, 24:1090–1097.

Röder, T., Müller, M., and Clausen, M. (2023). Geometrische relationen für die bewegungsanalyse.

Schwegler, J. and Lucius, R. (2016). *Der Mensch - Anatomie und Physiologie*. CNE Bibliothek. Thieme.

Wolff, D. (2018). *OpenGL 4 Shading Language Codebook*. Packt Publishing, Birmingham, 3nd edition.

Zhao, W., Feng, H., Lun, R., Espy, D. D., and Reinthal, M. A. (2014). A kinect-based rehabilitation exercise monitoring and guidance system. In *2014 IEEE 5th International Conference on Software Engineering and Service Science*, pages 762–765.