Methodological assessment of an electromagnetic motion tracking device

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Sammendrag

Denne studiens formål er å bestemme reliabiliteten til et instrument for tredimensjonal bevegelsesanalyse. Forståelsen av variasjon i målinger er basert på klassisk måleteori. To aspekter vedrørende reliabilitet har blitt undersøkt: instrument- og intrasubjektreliabilitet (test-retest). Hensikten med denne studien er å beskrive kvaliteter som stabilitet, repeterbarhet og nøyaktighet for det aktuelle instrumentet. Instrumentets sensorer blir sporet ved diskrete tidsintervaller (240 Hz) i et varierende lavintensitets elektromagnetisk felt som genereres av en antenne (senderen). Instrumentets posisjonsmål i ro i tre retninger (x, y og z) ble testet både ved at sensorene var fiksert i en testramme av tre, og på seks testpersoner uten nakkesmerter (gjennomsnittlig alder ± standard avvik (SA), 40.5 ± 9.9 år; range 29 – 54 år).

I testrammen ble en sensor plassert i posisjoner med en varierende avstand til senderen. Repeterte opptak ble tatt. Instrumentet gir posisjonsmål med svært lavt SA for alle opptak. Dette innebærer at instrumentet gir data med nesten ingen støy (< 0.04 mm SA for en sensor < 0.5 m til sender i testrammen). Resultatene viste at avstanden mellom sensor og sender var av stor betydning for størrelsen på systemets SA: økende avstand til sender økte SA i målingene. Tre sensorer ble plassert på de seks forsøkspersonene. Bare data fra sensoren som ble festet i pannen ble analysert i denne studien. Forsøkspersonene ble instruert til å reposisjonere hodet til en selvvalgt nøytral hodeposisjon med og uten bevegelse av nakken mellom hver reposisjonering. De seks forsøkspersonene viste et stigende SA ved økende lengde på tidsintervallet som grunnlag for beregningene, likevel var SA svært lave (< 0.6 mm SA for et tidsintervall på ett sekund). Variabiliteten i gjennomsnittlig posisjonsmål og SA var generelt svært små i x-retning og høyest i y-retning. Dette gjelder både for eksperimenter gjort i testrammen og med friske forsøkspersoner. Instrumentet gir avvikende gjennomsnittlige posisjonsmål ved introduksjon av metallobjekter som messing, bly og jern nær sensor. En aktiv elektrode for elektromyografisk registrering, Teflon og tegl påvirket ikke instrumentets posisjonsdata.

Når sensorer plasseres innenfor 0.5 m fra sender og mengden metall i testoppsettet er begrenset, i ro og minst 0.4 m fra sensoren, gir instrumentet posisjonsmål som er repeterbare og stabile til en grad som langt overstiger den klinisk interessante presisjonsgrensen.

Nøkkelord: elektromagnetisk bevegelsesanalyse, tredimensjonal nakkebevegelse, kinematikk

Abstract

This aim of this study is to determine the reliability of a 3D motion tracking device. The understanding of variation in measurements is based on classical measurement theory. Two aspects of reliability have been examined. That is instrument and intrasubject reliability (test-retest). The objective of this study is to describe characteristics such as stability, repeatability and accuracy for the present motion tracking system. The instrument tracks its sensors at discrete time intervals (240 Hz) in space in a varying low-intensity electromagnetic field generated by the transmitter (antenna). The instrument's position measures in three directions (x, y and z) was tested at rest both with the instrument sensors in fixed positions in a wooden rig, and on six test persons without persistent neck pain (mean age ± standard deviation (SD), 40.5 ± 9.9 y; range 29 – 54 y).

In the wooden test rig, a sensor was positioned at varying distance related to the transmitter. Repeated recordings were made. The instrument provided position measures with a very low SD for all recordings i.e. the instrument provides data sets with hardly any noise (< 0.04 mm SD for a sensor < 0.5 m to transmitter in test rig). The results show that the distance between sensor and transmitter was of great importance regarding the magnitude of the system SD i.e. increasing distance to transmitter increases SD in measurements. Three sensors were placed on the six test persons. Only data from the sensor positioned on the forehead were analysed in this study. The test persons were asked to reposition their head to a self-elected neutral head position with and without movement of the neck between each repositioning. An increasing SD with increasing time interval for calculation of SD was seen, still the variation were low (< 0.6 mm SD for a one second time interval). The variability in mean position measures and SD were generally remarkably low in x-direction and highest in y-direction. This was seen both in the rig and with humans tested. The instrument was affected by metallic objects such as brass, lead and iron by giving aberrant mean position measures when introduced close to sensor. An active electromyography electrode, Teflon and brick did not affect the instrument position data.

When sensors are positioned within a 0.5 m distance to transmitter and the presence of metallic objects are limited, at rest and at least 0.4 m away from the sensor, the instrument provides a repeatability and stability that exceeds the clinical limit of precision.

Key words: electromagnetic motion tracking device, three-dimensional neck motion, kinematics

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1. Introduction

1.1 Background

A basic tenet in the clinical examination of people with neck pain is to assess and map out human motion of the cervical spine is. It is a main concern to get a detailed description and understanding of human movement of the head and neck. There are some evidence that people with neck pain have a reduced range of motion and a more inaccurate repositioning than asymptomatic subjects (8;11;20;21;25). The ability of repositioning is shown to be independent of the range of motion in the spine measured from the skin area over vertebra Th 1 to S 1(34). Yet the literature regarding the possibility to distinguish people with chronic neck pain from asymptomatic subjects with their ability to reposition the head, is unclear (5;21;22;32;35).

A common opinion amongst practitioners is that humans with chronic neck pain show aberrant motor control during movement in the neck region when compared to healthy subjects. Their movements are often described as unsteady with a reduced ability to reposition the head (7). Based on the hypothesis that the cause of pain is instability in the neck region, the treatment is often active exercises to improve the ability of the neuromuscular system to increase the stability (10;27). Despite this expectation by therapists regarding chronic neck pain, the current literature is of poor methodological quality and show no well documented effective treatment (14;37). Kay et al (18) concluded that exercises have a role in treatment of both acute and chronic mechanical neck disorder and neck disorder plus headache. The benefit of each type of treatment is unclear and needs extensive research. The mechanism that causes the recovery is still unknown (ibid).

In the literature there is much focus on different patient groups' treatment effects or how these groups perform in various tasks, and considerable less focus on how and why active exercises affect the neuromuscular system. To better understand the treatment effects and diagnoses, neck pain needs to be examined on the basis of the theory of causality. It is therefore necessary to establish a method that describes neck function by a simultaneous mapping of different qualities of neck movement. In this study, the possibility to use electromyography (EMG) and weights added close to the instrument is checked.

For this purpose a reliable motion tracking instrument is needed. Such instrument will also be of relevance when assessing how exercises are performed in different subjects and studies. For instance this can reveal if the different results studies are due to difference in human performance or not.

1.2 Measurement of movement

The available systems for motion tracking are based on various technologies and have distinct qualities. Popular principles for motion tracking include mechanical devices, camera based systems, ultrasound, inertial systems and systems based on magnetic fields. In this study, a system based on magnetic fields was chosen because it presumably has a high sample rate and accuracy, is insensitive to occlusion and is drift-free.

The instrument for motion tracking used in the present study was Liberty (Polhemus Inc., Vermont). This instrument traces its sensors by letting an antenna (transmitter) generate a varying low-intensity electromagnetic field.

An electromagnetic field describes a situation where an electric and magnetic field appear simultaneously. Magnetic flux is a quantification of magnetism based on the density of the field lines per area. Magnetic flux can therefore change if the area or the density of the field lines changes. Electric field lines are most dense around objects with the greatest amount of charge e.g. close to the transmitter (26).

When using an instrument which bases its data on an electromagnetic field, there are two main concerns regarding errors of measurement. (i) With an increasing distance between transmitter and sensor, the density in electric field lines decrease. For this situation it is expected a gradually increase in variation in measurement with increasing distance to transmitter. (ii) When positioning objects close to the instrument, this will add other electromagnetic fields. Depending on the strength of these fields, this will have the possibility to confuse the sensor regarding where it is positioned in space because the magnetic flux is changed, and therefore aberrant position measures is likely to occur (ibid).

The effect of these events must be investigated systematically before it is possible to use this motion tracking device together with another instrument (EMG), and objects added gradually as a load to the head. Therefore this study introduces objects in a wooden test rig at different positions both related to the sensor and transmitter with the sensor fixed in marked positions. The intention is that this will provide information about whether it is possible to use this motion tracking device together with other instruments in the test setup without influence on the instrument's data.

The test setup of the wooden rig is quite similar to how McGill, Cholewicki & Peach (23) tested the system regarding object positioning. They reported only data from one sensor position (80 cm from transmitter).

Classical measurement theory was chosen to describing the sources of measurement error when using this instrument in the present test setup. This implies that to get as close to the true value with a measure, a strictly controlled experiment setup and repeated measures are needed to estimate measurement errors (9). In this study, a test-retest design was addressed to investigate both instrument and intrasubject[1] reliability. Mean and SD are basic statistical measures in this theory (ibid) and therefore used when analysing the present data set. In addition, visual analyses of the raw data are performed.

The objective of this study is to describe the instrument's reliability and validity. For that an instrument should be valid it must first be found to be reliable (25). In this study, reliability is described with the terms stability and repeatability. Stability is to

[1] Intrasubject reliability concerns actual changes in subject performance between measurements (9).

what extent the instrument reports the same position measure with time within recordings (29). No objects or new test interventions are performed during these tests. Repeatability is the variation in estimated mean position measures for files recorded on the same day and on different days. Repeatability conditions include: the same measurement procedure, observer, measuring instrument, used under the same conditions, in the same location and over a short period of time (3;4;9). Validity concerns the instrument's accuracy, i.e. is to what degree it is conformity of a measured position measure to its true value. To examine this quality an additional instrument assessed as a gold standard is needed (2).

In addition, different objects are introduced in the test setup to reveal if this affects the instrument reliability.

The following questions are addressed:

1. What is the variability of measurements when a sensor is completely at rest? Is this variability dependent on a changing sensor position in the test setup?

2. To what extent are objects of different materials affecting the measurement of a sensor position? Is the positioning of objects related to the sensor or transmitter of relevance?

When the instrument's sensors are applied on humans, additional sources of errors arise. A relevant source of error is that the sensor on skin might move slightly. Still, the most important factor is that we do not know the true movements of the person tested at rest.

To get information about the system's ability to report stability and repeatability in humans, they were asked to hold the head at rest in neutral head position. The movements recorded in these experiments were assessed as an expression of postural sway which is expected to appear in sitting (13). Regarding human experiments these questions are addressed:

3. What is the variability in position measurements when sensors are applied to humans who are instructed to hold a position of rest?

4. How large is the variation in mean position measure when test persons are asked to reposition the head to a self-elected neutral head position?

2. Method

2.1 The instrument

Liberty (Polhemus Inc.) is a system for electromagnetic motion tracking. The system is non invasive. The transmitter and sensors all consists of three orthogonal coils covered by a rigid plastic shield and corded to a main unit. The sensors are passive devices without any active voltage. The transmitter is an antenna which generates a varying low-intensity electromagnetic field. This field is sensed by the sensors and whereby the sensors orientation and position is recorded relative to the transmitter at discrete time intervals. The system provides data sets of six degrees of freedom defined as three position measures (cartesian coordinates) and three orientation angles (Euler angles).

Liberty 240/8 (Polhemus Inc, Colechester, Vermont) was used. This instrument has the possibility to use four sensors simultaneously. The sampling frequency is 240 Hz regardless of the number of sensors connected. The manufacturer states that the system has a range of 90 cm from transmitter with a static accuracy of 0.76 mm SD for each of the three directions (x, y and z). The latency is low (3.5 ms). The resolution is stated to be 0.04 mm at 30 cm distance (1).

The system has a built in self test for system calibration. A green light indicates no distortion and no further calibration is needed (1). A steady green light shone under the recording of all data files included in this study.

2.2 Wooden rig

2.2.1 Test setup

When testing an instrument which is based on electromagnetic tracking of sensors, it was regarded important to make the testing environment free of objects that could

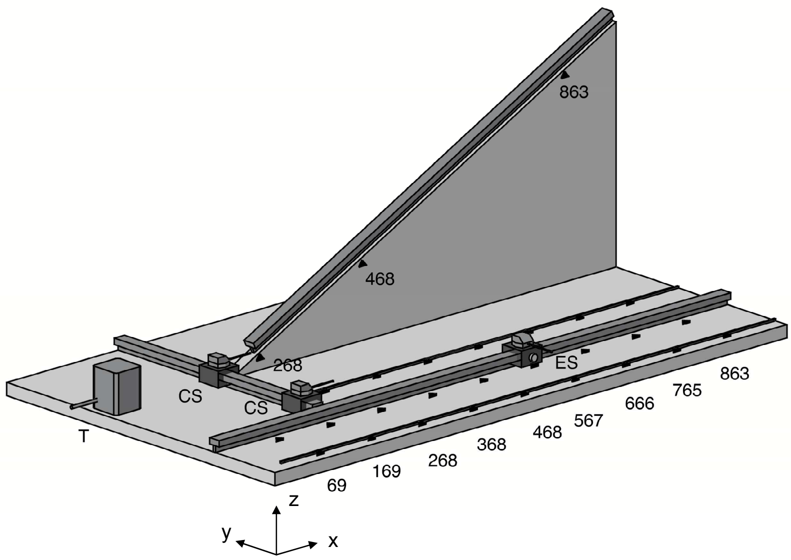

Figure 1: Test setup in the wooden rig. The instrument with the transmitter (T), two control sensors (CS) and one experimental sensor (ES) positioned in test setup. On the outer side of the track in x-direction, a ruler with nine marked positions as the distance to transmitter is drawn. These nine ruler positions describes all positions in the setup. The experimental sensor is placed in all marked positions in x-direction and on inclined plane for recordings. Places for object positioning are marked on two lines parallel to the track in x-direction. The sensors are corded to a main unit (only 5 cm of the cords are drawn). Numbers are in mm and give the distance to transmitter in x-direction.

affect the field and thereby the instrument. McGill, Cholewicki & Peach (23) reported a deviation in the system's mean angular measures when a wooden block was placed above the sensor. The difference in mean angle was <0.1° from a measure in a clean field.

To assess instrument qualities such as stability, repeatability and accuracy a specially constructed rig was designed with as few objects in it as possible (Figure 1). Since the difference described above was small and only appeared when positioned above sensor (ibid), wood was used when constructing the rig without concern of aberrant data.

In addition to the instrument itself, no metal (e.g. computer, instrument main unit, weights) or non metal objects (e.g. other tables, walls) were placed in the rig and a 1.5 m distance to it during start of all experiments. Objects for experimental use (Table 1) were placed over two meters from the test setup.

The rig was placed on a wooden table and the transmitter and three sensors were positioned in it. Each sensor was fixed on a plastic «wagon», and the transmitter was fastened to the wooden board with plastic screws. The three «wagons» could be moved in tracks or fixed in positions using a plastic screw.

Two of the sensors were kept in the same position on the track in y-direction during all tests (control sensors). The third sensor (experimental sensor) was moved along two tracks i.e. the one in x-direction and the inclined plane. The experimental sensor was moved to marked positions and fixed with the plastic screw on these two tracks in subsequent recordings (Figure 1).

It is expected that the system will be affected by metal or other objects that generate electromagnetic fields (1;23). Experiments where different objects (Table 1) were placed at the marked positions along two lines on the outer and inner side of the track in x-direction (Figure 1), for different sensor positions along x-track, were carried out. The different objects were introduced systematically in subsequent experiments.

During all recordings of a sensor at rest, the sensor or table were neither moved nor touched. A sensor with the possibility to make timestamps in the recordings was connected to the main unit and used for this purpose.

It would have been of interest to systematically check if the sensor behaved in the same way during movement as at rest. We did not manage to make a rig that fitted this purpose. When moving the «wagon» along the track a sway that was bigger than the expected system variability at rest was possible because of wobble between «wagon» and track. In addition we were not able to find a machine that could move the sensor without affecting the system. Such machines are often made of metal and with motors that generate electromagnetic fields. This was considered incompatible with the purpose. Hence, no reports of measurements of moving sensors are reported.

2.2.2 Procedure

Data used for describing accuracy, stability and repeatability were recordings with the sensors at rest and fastened in definite positions along x- and z-track, of varying length (from three to thirty minutes). In order to ease later analysis, the data recorded was organized as described in Appendix 1.

Stability

Stability was tested in recordings lasting 30 minutes (min), recorded in a setup with no objects except those described in Figure 1. Variability between following single position measures were analysed in frequency distributions and plots. Stability was understood as the instruments ability to report the same position in space with time. Time intervals lasting from 0.0125 seconds (s) to 30 min was used to get overview of the development of the mean position measures and the variability (SD) connected to this estimates. The uncertainty in these estimates was evaluated on the basis of the range in mean positions and degree of variability (SD). The aim of this analysis was to examine the smallest time interval where a stable estimate of mean position were obtained, and an idea of the uncertainty connected to these estimates.

This procedure was carried out in nine different files recorded from nine different positions in the test setup. All time intervals were started in the beginning of the recording.

Repeatability

Repeatability was tested with repeated recordings on the same day and between days. Mean position measures based on a one second recording and the variability (SD) related to this estimate were the basis for the analysis of repeatability.

The manufacturer states that the system is affected by metallic objects (1), and one study reports that other non metallic objects do the same (23). To systematically investigate the effect on objects introduced in the electromagnetic field, different types of objects (Table 1) were introduced at different positions related to both the sensor and the transmitter. These objects were positioned in marked positions along the two lines on each side of the x-track which positions corresponded to the sensor positions along this track (Figure 1). Objects were at complete rest in the time intervals used for analysis.

Table 1: Objects introduced in test setup.

Type of object	Weight (g)	Shape	Physical characteristics (mm)
Iron	500	Disc	r=37, h=14 *
Lead **	333	Line (two)	1: 5.5x10x111 2: 11x11x260
Brass	500	Disc	R=62.6, h=5.5
Teflon**	1975	cylinder (two)	1: r=11.5, h=155 2: r=27, h=325
Brick	2400	block	85x88x228
EMG electrode (Delsys)	8	block	20x6x40

* whole in centre of disc, d=26mm.
** two weights were regarded as one and always positioned together.

The different events (e.g. a certain type of object in a certain position) were marked in the recordings with a timestamp. As a measure of degree of distortion induced by the different objects, mean position measures and SD were calculated for the first second in the recording and compared to measures from the corresponding position in a test setup with no objects introduced.

The human ability to repeat positions were tested when a sensor was moved and repositioned seven times between two marked positions along the x-track. A seated test leader moved the «wagon» with the attached sensor along the track and repositioned it in the marked positions. The test conditions were developed so that the working conditions were expected to be the same despite changing positions along the track in x-direction. The human performance error in repositioning was therefore expected to be constant for the different positions. Difference in mean position measures was considered the sum of two components: the system's repeatability and a human error when positioning the «wagon». Human repeatability was analysed for each position by investigating the range in mean position measures between the seven recordings.

Accuracy

Accuracy was tested by comparing the position measures in three directions made by the instrument to position measures made with a metric ruler. Absolute accuracy e.g. distance between transmitter and sensor with a sensor placed in two different positions, were measured. As foundation for comparison, three measurements were made both with Liberty and the ruler (resolution 1 mm) for each position. For Liberty, each of the three position measures was estimated over a one second recording. The mean position measure based on the three subsequent measures was used for comparison between the two instruments.

Data collection and calculations regarding accuracy were carried out. These data showed that the practical implications related to measurements made with the ruler were major particularly in z-direction. These measures were assessed to be too unreliable to precede the analysis. These data are therefore not shown in this study.

2.3 Human experiments

2.3.1 Subjects

Six test persons were recruited among students and staff on the Section of Health Science, University of Oslo. The five female and one male (mean age ± standard deviation (SD), 40.5 ± 9.9 y; range 29 – 54 y) were all free of neck pain at present. Two had a history of neck pain, but pain had faded out years ago.

This study was not submitted for the regional ethics committee because it was considered to be a methodological assessment rather than a biomedical study. In addition, previous similar versions of the instrument tested has been used for scientific purposes over the last 10-15 years (15), and therefore regarded as an established instrument for motion tracking.

2.3.2 Test setup

Three sensors were placed on the test persons: over C7 prosessus spinosus, in the middle of the forehead aligned with the bridge of the nose and over manubrium sterni. The transmitter was positioned on the left side of the test persons at level with their head. This positioning made the sensors remain within a 50 cm distance to transmitter at all times during the experiments.

The test persons were seated in a wooden chair, sitting tall with their back against the backrest, both feet on the floor, sitting on one's hands and with the head facing straight ahead. The test person's vision was occluded. The test persons had no feedback of performance during experiments.

The test persons were asked to say «yes» when neutral head position or a position of flexion/ extension was achieved. The test leader gave instructions on when to rest or move the head to the next position.

The test sequence was similar to what was described by Revel et al (31) when testing head movement with another type of instrument.

Recordings were made on two subsequent days. Recordings from the second day were used in analysis. For this study, only data from the forehead sensor were analysed. This sensor was chosen because it was placed on the body segment with the most degrees of freedom and therefore the greatest variation of the three was expected to be found here. In addition further experiments with this instrument will be performed to analyse head movements. Hence, measurement properties when sensors are applied to the head are of importance to describe.

In these experiments, the head were only moved in the direction of flexion and extension between repositioning. Only data when the sensor mounted on the head was at rest were analysed.

2.3.3 Procedure

Two different experiments with humans were carried out. Human ability to reposition the head to a self-elected neutral head position was tested in both experiments. The only thing that distinguished the two was what happened between the repositions. In experiment one, no movement between repositioning in neutral head position were instructed, while in the latter the test person was told to move the head in the direction of flexion and extension between repositioning to the self-elected neutral head position. Three succeeding series of test one and two with two repositions in each was recorded for each test person. See Appendix 2 for details.

Stability in instrument position measures were examined by estimating the mean position measure in the three directions for time intervals ranging from 0.025 to 2.5 s. This was performed on nine[2] data parts for each time interval per person. Data from experiment one were used. The SD for these nine position estimates for a sensor at rest for each time interval was the fundament for the mean SD. The mean SD was plotted with time to visualize the effect on variation in estimated position measures with time.

Repositioning was tested as the test person's ability to reposition the head to the self-elected neutral head position. The mean position in x, y and z were estimated for a time interval lasting for two seconds. The six repositions per test person per experiment were plotted in the frontal-, transversal- and sagital plane to get a visualisation of the difference in reposition estimates among these six test persons.

In order to ease later analysis, the data recorded was organized as described in Appendix 2.

[2] Each test person positioned the head in neutral head position three times in each series. There were carried out three subsequent series in each experiment per test person i.e. nine times in neutral head position.

2.4 Data processing

2.4.1 Data acquisition software

Due to systematic data loss in the data acquisition software supplied by the manufacturer, new software was made and tested for this. No data losses were found. The data acquisition software used did not provide real time visualization i.e. the test leader did not get information about sensor positions or the test persons performance during the process of collecting data. Hence, all experiments were carried out without knowledge of amount of precision in performance.

2.4.2 Analysis

The analysis in this study was carried out using the instruments position measurements and not angles. This is because Pearcy & Hindle (28) reported an increasing inaccuracy with increasing angles measured at the same distance from transmitter.

MATLAB and Microsoft Excel were used for doing calculations on the data sets.

All experiments were led and carried out by the author. When EMG was used in experiments the same person assisted in all experiments.

Analysis shown in this study represents only a selection of the recordings analysed (Table 2). When several files are analysed, two different things have been done. For the experiments with the test persons all analysed recordings have been shown, for the instrument test consequently those recordings with most variability have been shown.

Table 2: Overview of number of recordings analysed. Recordings sorted after the term they were sampled to describe.

	Term	**Number of analysed recordings**	**Number of different positions**	**Number of sensors analysed in recording**
Test rig	Stability	9	9	1
	Repeatability - system	9	1	2
	Repeatability – objects	14	4	2
	Repeatability – human along track	4	7	1
Test persons	Stability	36	3 *	1
	Repositioning	36	3 *	1

* the test persons are instructed to reposition the head to neutral head position three times.

3. Results

3.1 Instrument testing

3.1.1 Stability

For a sensor positioned 862 mm from the transmitter (Figure 1) range over a 30 minutes recording for position measure in one direction was of almost 4 mm (Figure 2 and Figure 3a). The position measures for the two time intervals (30 minutes and 1 s) in Figure 3 show a normally distributed variable.

For investigating stability with time, the effect regarding the number of observations needed for a stable position measure, calculations of mean position and SD was made on data sets of varying time intervals.

As seen in Table 3 only marginal differences in mean position measures (<0.4mm) were seen in all three directions when calculations were performed on twelve different time intervals. If the time sample of 0.0125 s was omitted, the differences in mean position measures were markedly reduced (<0.1).

The SD was small in all three directions (< 0.6 mm). The SD was least in x-direction

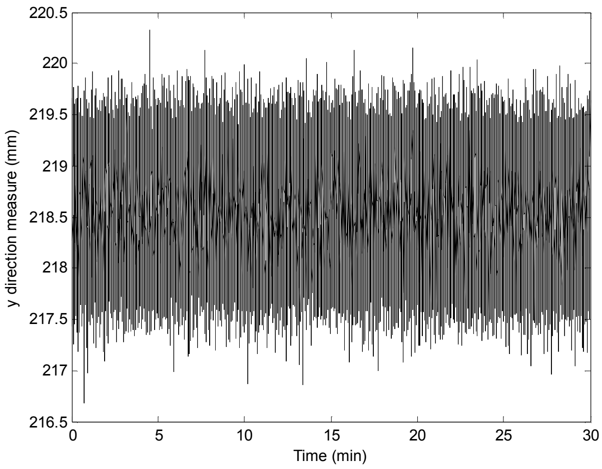

Figure 2: Stability in subsequent position measures. Raw data for a sensor placed 862 mm from transmitter (in y-direction). Position measures in y-direction over 30 min shown.

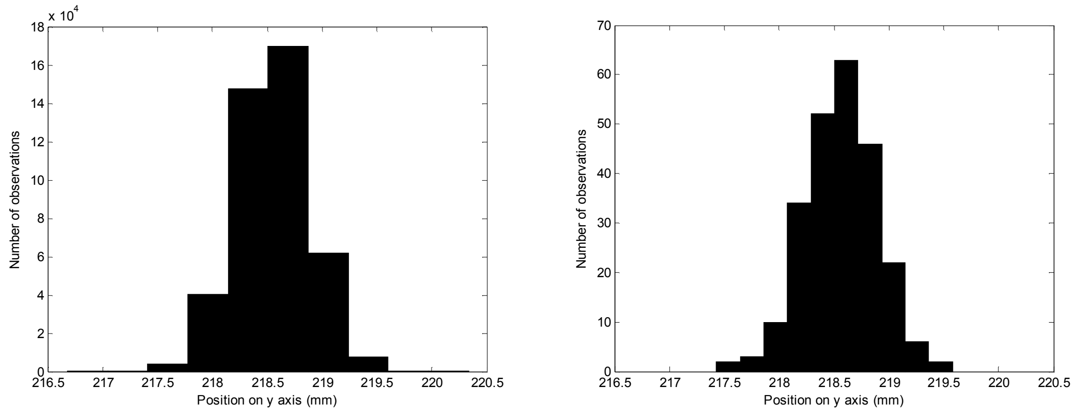

Figure 3: Distribution of subsequent position measures. Distribution of subsequent measures of position in y direction shown for the first (a) 30 minutes and (b) the first second for a sensor placed in a position approximately 862 mm from transmitter (same recording as in Figure 2).

and about three times larger in y- and z-direction. The range in SD for the twelve different time intervals was considerably larger than the variation within each interval. The highest SD were seen with the shorter time intervals (<0.1 s). Nevertheless, this increase was small, i.e. SD was less than 0.2 mm for all directions.

Similar analyses were made for recordings from all nine positions on the track in x-direction (Figure 1). Only the farthest position to transmitter was shown. No drift or baseline shift was observed in any of the three directions for these nine 30 minutes' recordings. The other eight files showed the same tendency for both stability and variability but of a smaller magnitude for all three directions than showed in Table 3, Figure 2 and Figure 3.

Table 3: Stability in position measures estimated on varying time intervals. Position measures calculated on data sets of varying time length for a sensor placed 862 mm form transmitter. Position measures reported in all three directions (x, y and z). Arithmetic mean and SD are given. Data sets for calculation always start at the same moment in the file. Sensor is positioned about 862 mm from transmitter. No other objects in the test setup. Data given in mm.

		X		Y		Z	
Time interval (s)	**Number of observations**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
0.0125	3	862.53	0.11	218.26	0.31	29.71	0.54
0.025	6	862.41	0.17	218.63	0.45	29.85	0.55
0.05	12	862.39	0.17	218.58	0.36	29.81	0.44
0.1	24	862.4	0.14	218.54	0.29	29.87	0.44
0.5	120	862.4	0.12	218.55	0.35	29.84	0.41
1	240	862.4	0.12	218.56	0.33	29.84	0.42
5	1 200	862.38	0.13	218.58	0.33	29.85	0.42
30	7 200	862.39	0.12	218.56	0.33	29.84	0.38
60	144 000	862.39	0.12	218.56	0.33	29.84	0.37
300	720 000	862.39	0.12	218.56	0.33	29.83	0.37
900	216 000	862.38	0.12	218.56	0.33	29.81	0.37
1 800	432 000	862.38	0.12	218.55	0.33	29.8	0.37
Mean		862.4	0.13	218.54	0.34	29.83	0.42
Max		862.53	0.17	218.63	0.45	29.87	0.55
Min		862.38	0.11	218.26	0.29	29.71	0.37
Range		0.16	0.06	0.37	0.16	0.16	0.18
Range without 0.0125 time span		0.03	0.05	0.09	0.16	0.08	0.18

Analysis with varying time intervals has also been made with data parts selected from various parts of a recording to ensure independence of the data sets. The data parts were selected at random within the file. Within a file very small differences (< 0.01 mm) were found when comparing mean position measure and SD calculated from different parts of the data set.

Sensor at increasing distance to transmitter

The variation in position measures in all three directions increased with increasing distance to transmitter (Figure 4). The SD for sensors in all positions within 90 cm from transmitter was below 0.5 mm. Again, SD in z- and y-directions were larger than

(a) (b)

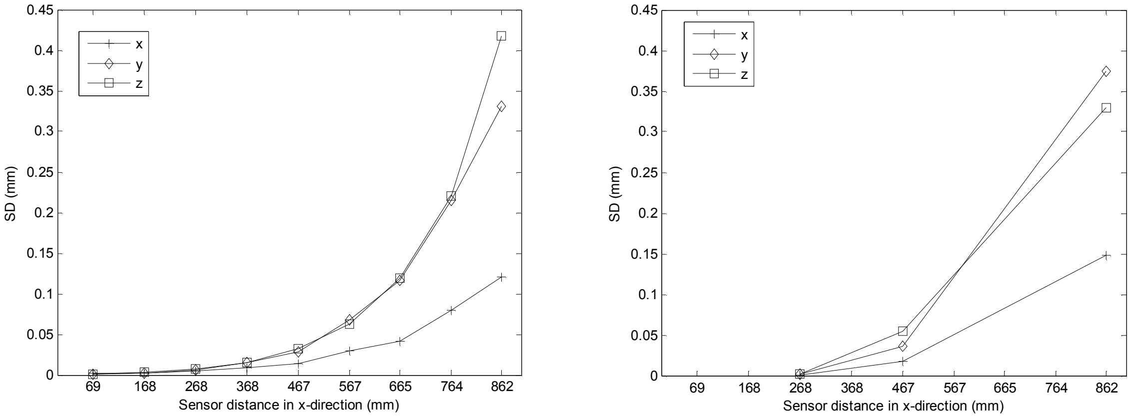

Figure 4: SD for a sensor positioned at increasing distance to transmitter. SD are shown for each position in all three directions and are drawn as separate lines. SD calculated on a time interval of one second. Sensor positioned at (a) nine different positions along an orthogonal track related to transmitter and (b) three different positions on an inclined plane. The three positions in (b) are at same distance from transmitter in x-direction to those in (a) (Figure 1).

in x-direction. Furthermore, there was only a marginal increase in variability for sensors placed less than 50 cm from transmitter.

The tendency Figure 4 displays have been repeated in all recordings analysed for this study.

3.1.2 Repeatability

No objects in test setup

The system repeatability was tested for a sensor in a position approximately 15 cm from transmitter between files from the same day and files from different days. The recordings were made on three subsequent days. The test setup was not moved nor changed between and during these days with repeated recordings.

For files recorded on the same day, the range between average position measures in the three different directions was all less than 0.1 mm. When recordings from three different days were compared, the range had doubled (< 0.2 mm). This represents the instrument's system error.

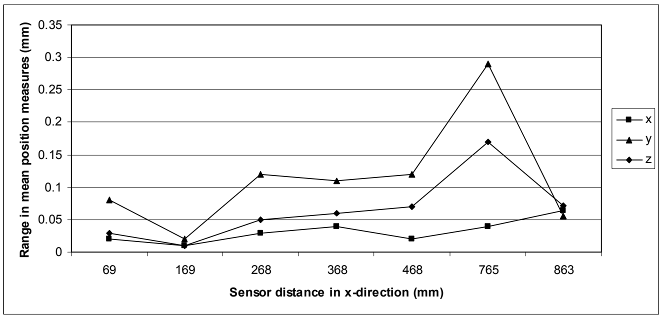

Figure 5: Repeatability for a sensor repositioned seven times in each position. Range in mean position measures for a sensor manually repositioned between two and two positions on the track orthogonal to transmitter. Positions described by distance in x-direction (mm) to transmitter (Figure 1). Mean position measures were calculated on a time interval of one second. No other objects in experiment setup. Data are given in mm.

When repeatability was tested for a sensor moved between two positions on the orthogonal track to transmitter, a human source of error was added. The range in mean position measure when a sensor was repositioned seven times showed almost the same magnitude as the range in calculations of mean position measures with varying time intervals (Table 3). This can imply that the human source of error was quite small, and that the range in position measure was due to increasing measurement variation with increasing distance to transmitter (Figure 4).

Figure 5 shows that the range for all positions except 765 mm in x-direction from transmitter was very small (< 0.1 mm). This position had a higher range in all directions. The deviation in mean position measure is still very small (< 0.3 mm). Range in SD when a sensor is repositioned is absent (< 0.01 mm).

With objects in test setup

Two different types of experiments were performed with objects in test setup. In the first, the sensor was positioned in one position (268 mm) and objects of different materials were introduced at different positions. In the second, the sensor was positioned in three different positions with increasing distance to transmitter and an object that affected the system to a very small extent were introduced in the test rig. Objects were positioned alongside the track in x-direction both on the outer and inner

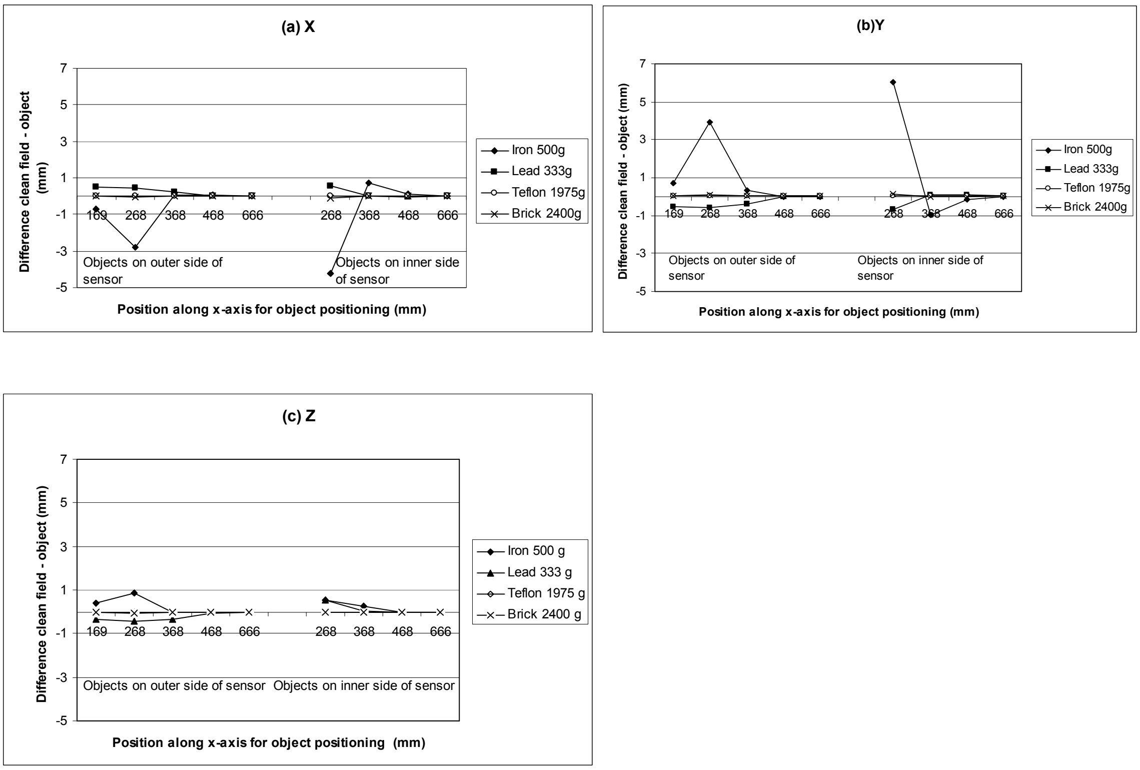

Figure 6: Objects in test setup at nine different positions in proportion to sensor. Sensor positioned 268 mm from transmitter in x-direction. Mean position measures calculated on a time interval of one second. Four objects (two metallic, two non metallic) were introduced. Difference from measure made in test setup without any objects drawn.

side of the track, see Figure 1. Both Figure 6 and Figure 7 display the difference between position measures with object versus measure from a field with no objects.

Figure 6 displays the most relevant objects and the pertaining changes in mean position measures for a sensor in the position 268 mm from transmitter. Lead and iron affects the instrument by giving aberrant position measures when they were positioned close to sensor both on the outer and inner side of the x-track. Non metallic objects such as Teflon and brick did not show to affect the system in the same way. Even when positioned very close to sensor, the deviation for brick and Teflon were smaller than the system's resolution (less than 0.04 mm).

Brass was also tested and affected the system a lot more than iron and lead with up to 13 mm deviation to measure in field without objects. A human arm, with and without an active EMG electrode, did not influence the test results, neither at rest nor while moving (data not shown).

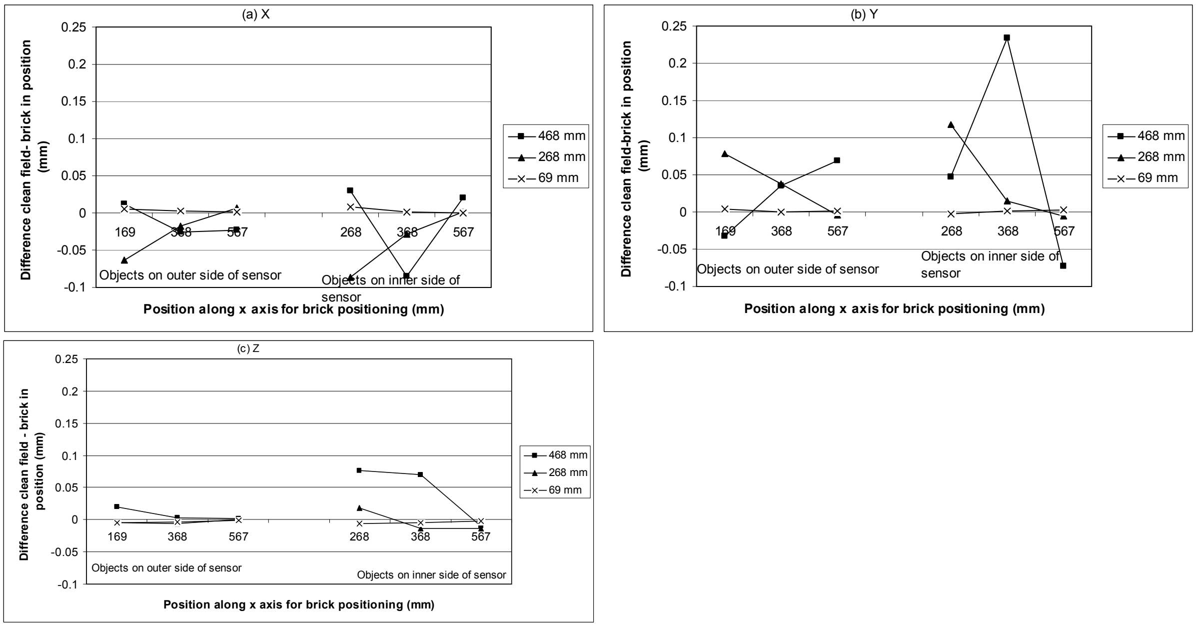

Figure 7: Object in test setup with sensor at three different positions. Brick in different positions related to sensor. The object is positioned in the same positions for three different sensor positions along the track in x-direction. Mean position measures calculated on a time interval of one second. Difference between measure without object in test setup and with brick in actual position reported. The brick were positioned in six different positions, three on outer and inner side of sensor.

When a 2.4 kg brick is introduced in different positions related to a sensor the deviations in position measures from a clean field is small (< 0.25 mm) (Figure 7). There was a tendency towards an increased deviation in measurement with the sensor's increasing distance to transmitter. E.g. for sensor 468 mm from transmitter the difference was about 0.08 mm compared to less than 0.001 mm for a sensor 268 mm from transmitter.

Measurements of mean sensor position when the objects were introduced about 40 cm from the sensor (e.g. for a 500 g metallic load) did not bias the sensor data considerably more than the system varibility for the present sensor distance to transmitter.

The aberrant data when different objects were positioned in the test setup was shown to be repeatable. Repeatability was found in five occasions where the same trial was replicated. This was valid for objects at rest among different files recorded on the same

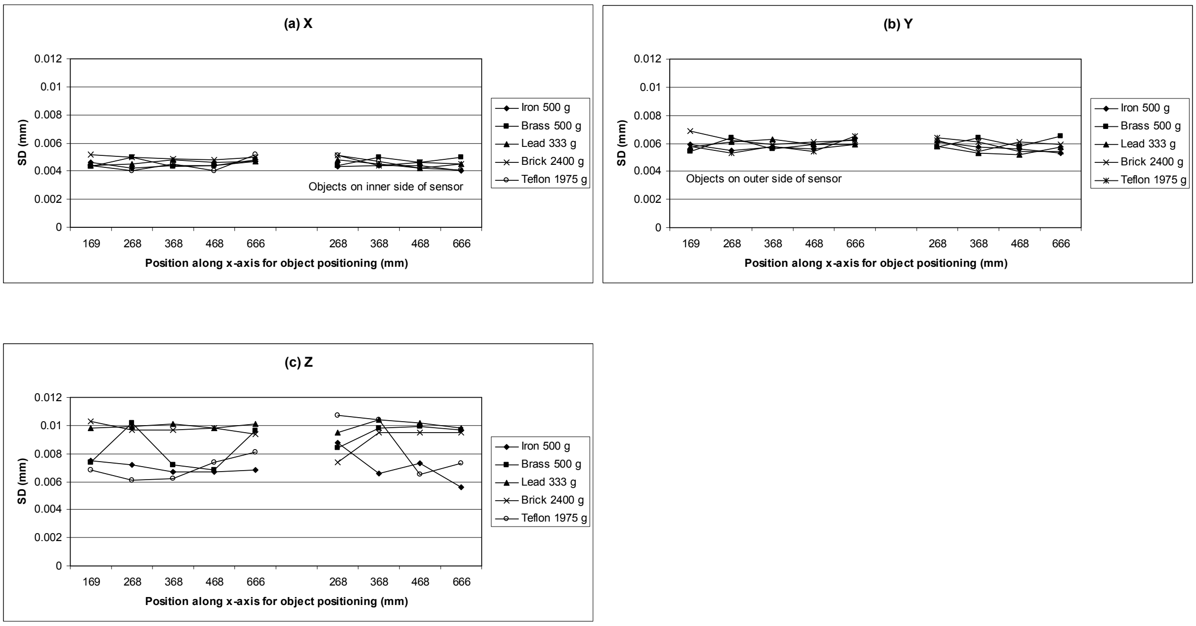

Figure 8: Variability and different objects in test setup. SD when different objects were positioned in nine different positions in proportion to senor. Sensor positioned 268 mm from transmitter in x-direction. Figure 5 is based on the same data set.

day both when the system has been switched off between recordings and when it has not.

The SD related to the mean position data did not rise when objects were introduced in test setup (Figure 8).

3.2 Human experiments

3.2.1 Stability

The test person's ability to hold their head at rest in neutral head position was assessed as an expression of stability.

The variation (SD) increased with an increasing length of time interval. For shorter time intervals (<0.25 s) the variation was almost of the same size as in the test rig (Figure 9). With increasing time interval, the variation increased considerably more than in the rig. The variation was least in x-direction both in test rig and among these test persons and was relatively small for all time intervals (compare to Table 3).

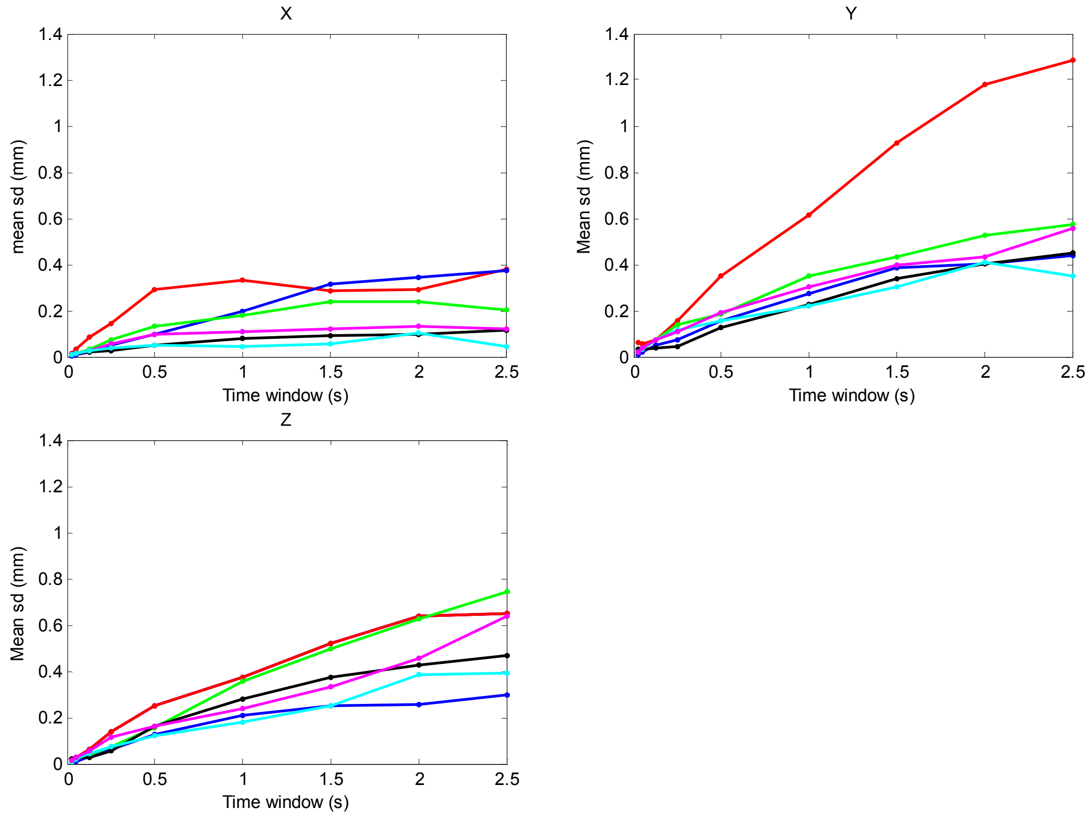

Figure 9: Varying length of time interval for estimation of mean SD. Data from nine repeated recordings in neutral head position for the six test persons were used as basis for estimations. The SD estimated on these nine data sets, for nine different time intervals ranging from 0.025 to 2.5 s, were the basis for the mean SD for each of the nine time intervals. The six test persons are coded with a colour each.

Hence, introduction of human performance in maintaining a stable position introduced a manifold increase in variation when a time interval of 1 s or more was used.

3.2.2 Repositioning

The differences in mean position measures when head were repositioned in neutral head position had least dispersal in x- and z-direction, and greatest in y-direction (in the plane of flexion and extension). This was consistent both for the experiments with and without instructed neck movement between repositioning (Figure 10).

Human ability to reposition the head to a self-elected neutral head position was better when the test person not were asked to move the head between each repositioning (Figure 10).

The only difference between the two experiments was that the magnitude of the reposition error was greater with movement between repositioning of the head than without.

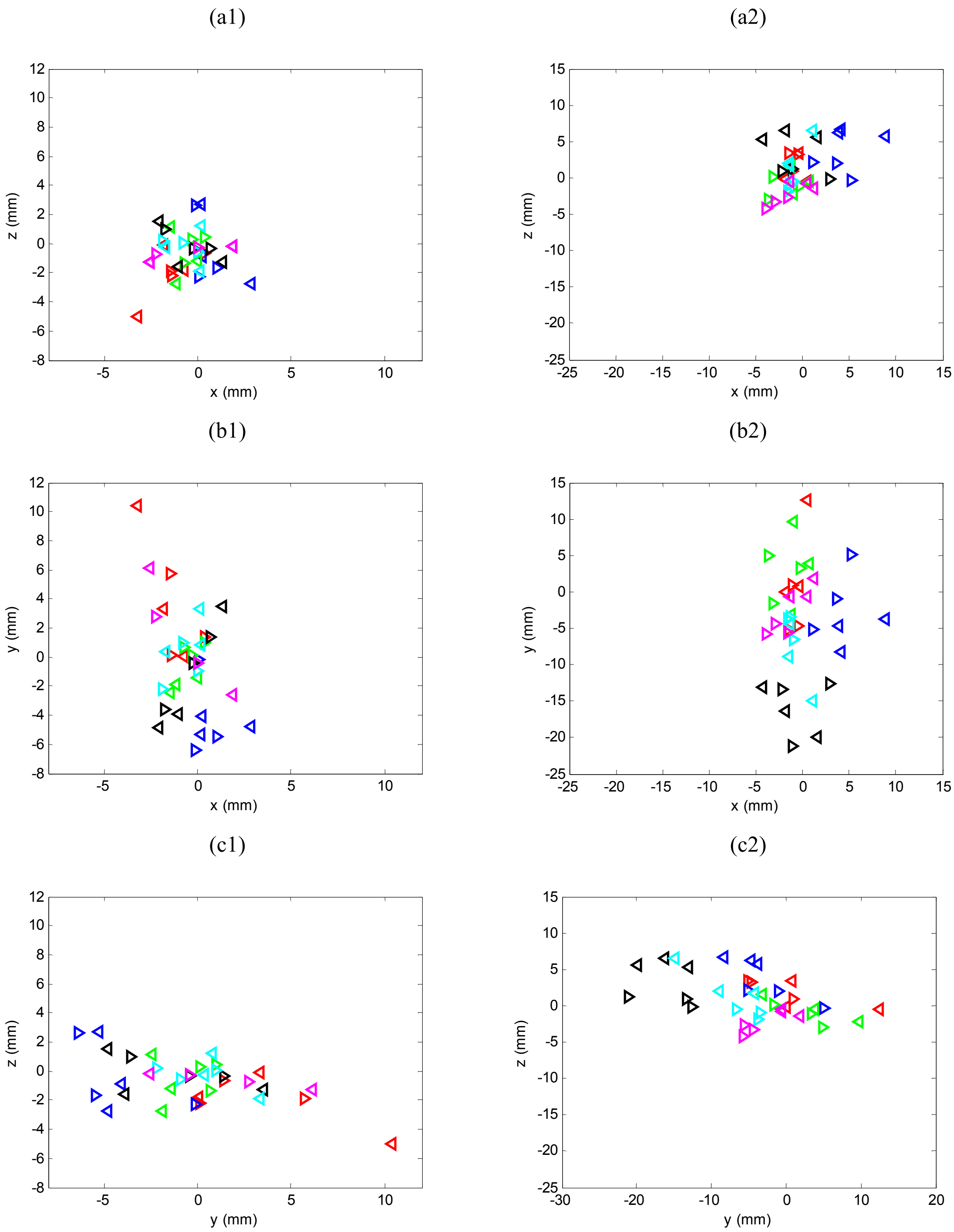

Figure 10: Repositioning of the head. Difference between mean positions at self-elected neutral head position and two subsequent repositions from a self-elected neutral head position. Mean position measures were based on a time interval of two seconds. Both data from experiment one and two shown: (left panel) rest in neutral head position between repositioning, and (right panel) with instructed movement between repositioning in direction of flexion and extension. Three series with two repositions in each for all six test persons are shown. The first reposition is marked with > and the second with <. Deviation in (a) frontal-, (b) transversal-, and (c) sagital plane are shown. The six test persons are coded with a colour each, and are consistent with Figure 9.

4. Discussion

4.1 Stability

The results on the instrument's stability imply that the system is stable over at least a period of 30 min in all three directions. The estimated mean position measures and its variability were remarkably stable among the twelve different time intervals. If the shortest time interval was removed from the analysis, the differences regarding mean positions were markedly reduced (range <0.1 mm). This suggests that a time interval for estimating a position with the same variability as for the longer intervals (up to 30 minutes) can be as short as 0.025 s. With this instrument's data acquisition frequency, it would therefore be reasonable to set the length for smoothing to approximately six observations to get a stable estimate of positions in space. This time interval balances noise attenuation and temporal precision well.

Increasing the distance to the transmitter increased the variability in the estimated mean position measures. The magnitude of the variability in mean position measures for each direction when sensors are closer than approximately 0.5 m to the transmitter is not larger than the system's resolution (0.04 mm SD at 30 cm).

The results from the test rig states that the position measures have a very low variability for all recordings within 90 cm from transmitter with 0.42 mm SD at 90 cm (Figure 4) is the highest variability in a clean field reported in this study. The variation for the shorter time intervals (<0.5 s) was also small for all test persons; they were in fact as small as in the test rig. This consolidates the same result for the test rig, that this instrument has a stable signal and very little noise. This is an essential quality with a motion tracking device when planning at using the system on sensors while moving.

When sitting, the head is not in a constant position with time (6;13). It has a low frequent movement which is so small it is difficult to see with the naked eye. This is called postural sway (13). For standing, postural sway has a slow moving dynamic response (< 2 Hz) (ibid). It is expected that sitting has a similar response. Therefore the length of the chosen time interval for calculation of mean position measures must be evaluated. The frequency of movement performed by the six test persons when asked to hold a position at rest is quite low (approximately 1 Hz, found with visual analysis) and may therefore be explained by the phenomenon of postural sway. Essential tremor is a common movement disorder affecting 5% of the population over 65 years, and has a reported frequency of between 4-12 Hz for both postural and kinetic tremor (19). In these persons the tremor are most often manifested in the hands, but can also affect the head movements (ibid.). For psychogenic tremor the frequencies are more uncertain but Raethjen et al (30) reports no frequencies less than 4 Hz. Michaelson et al (24) reported that people with chronic neck pain showed disturbances in postural control, described as increased changes in centre of pressure, when tested in standing. It is therefore likely to believe that tremor has at least a double frequency of postural sway. If a time interval has the possibility to discover sway, than tremor will be revealed. To reveal pathogen movement, the time interval for establishing a position should therefore be of at least one second.

In the present analysis, a two second time interval was used to make sure the sway was detected because of the expected low frequency in sway. There was a clear tendency of increasing variability with an increasing time interval for the six test persons. This compared with a visual analysis of changing position with time, can be an indicator that these data describes the head's movements in postural sway.

The magnitude of the variability found in the rig and among the best performing humans is approximately of the same size. The test persons performing with the least variation show approximately the same variation when using a two second time interval for estimation as shown in the test rig for a sensor at a 90 cm distance to transmitter. The difference lies in the development in the variability with varying time interval. In the rig the variation is shown to be remarkably stable and decreasing with a longer time span for estimation (Table 3). Among the six test persons it is shown a marked increase in variability with an increased time interval (Figure 9). It is likely to address this increase in variability to the test person's varying ability to hold the head at complete rest with time, because the instrument has already been tested and found to be stable with time.

The length of the time interval chosen for estimating mean positions is closely related to the phenomenon of investigation. Two different purposes and thus different intervals will exemplify this. (i) To state where a sensor was at a given time, only a time interval of 0.025 s is needed. (ii) To get an understanding of human stability, a time interval that exceeds the frequency of the movement expected at rest should be used. Postural sway has an expected frequency of < 2 Hz (13). A time interval of 1-2 s will be useful.

4.2 Repeatability

The instrument provides repeatable data for data sets recorded on the same or subsequent days. Metallic objects affect repeatability of position measures (Figure 6).

To check the instruments sensitivity to objects in the field, different objects (Table 1) were introduced in subsequent experiments. As expected metallic objects such as brass, lead and iron affected the system by giving aberrant mean position measures when introduced close to sensor. The deviation in mean position measure compared to data from a field with no objects, varied among the different types of metallic objects. It is unclear, from this data set, whether this difference is due to the type of metal, shape of the present object or unpunctual object positioning related to sensor.

Differences in mean position measures when compared to a measure from the same position without objects were both dependent on the sensors distance to transmitter and the objects distance to sensor. Objects close to transmitter affected the position measures less than when positioned further away. The deviation decreased relatively fast with increasing distance between object and sensor. McGill, Cholewicki & Peach

(23) reported the same tendencies. They explained these results with the nature of the electromagnetic field lines, and the current flow when objects are introduced in these fields.

Analyses show that the variability was not increased when metal objects were introduced. This means that it is not possible to look for aberrant position data by controlling for increased variation in measurements. Metallic objects affect the system by reducing the systems accuracy i.e. the system believes that the sensor is in another position in space.

The present data set suggests that it is possible to position small metal objects in the test setup as long as they are: (a) at least 40 cm from the sensors, (b) the amount of metal is limited and always less than 500 g and (c) the metal object are at rest at the time interval used for calculation. Use of computers (and other devices that generates electromagnetic fields) was not a problem as long as they were positioned at a 1.5 m distance to sensors and transmitter.

An instrument which is based on tracking of sensors in an electromagnetic field is vulnerable to objects that affect the field. When using an instrument based on this technology is it of great importance to have control over all objects in the testing environment. If this is not possible, an instrument based on another technology should be preferred because of the risk of getting aberrant data.

Based on the results in this study, it is expected that the variability in measurements are mostly dependent on the distance to transmitter (Figure 4). However, position measures are affected when objects are introduced and this affection is expected to increase with sensor’s increasing distance to transmitter (Figure 7). It is likely that this precision error is caused by changed density in the field lines when additional electromagnetic fields are introduced (26).

4.3 Accuracy

Accuracy is a property that is closely related to a system's veracity. A measure instrument should be tested against a gold standard to be considered accurate. Our attempt to do this did not succeed because we did not have another instrument with a comparable resolution and user-friendliness as the current system tested.

One study have documented the accuracy in an earlier version of this instrument where the transmitter was mounted on the test persons body (28). Swinkels & Dolan (33) tested an instrument version with similar transmitter positioning as I have tested, and they claimed that the instrument is accurate. No control against another instrument is described in this study (ibid.). Yet another have used the same system as a control measure when testing another motion tracking instrument (15).

In the first version of the system the transmitter was mounted on the test person. These studies (16;23;28;36) are not of complete comparison to the present version tested. The manufacturer has examined the static accuracy of the system (1). Except for this, no experiment of accuracy measured against a control measure on versions of the present instrument where the transmitter not is mounted on the body was found. Such an experiment would be of great interest because that an instrument shows good repeatability is no guarantee for accuracy and thereby valid measures (9).

Even though the instrument was found to provide stable and repeatable position measures for recordings lasting for up to 30 minutes, the built in self test of the instrument was found to be useless for detecting inaccurate position measures with our level of accuracy. Differences in mean position measures when comparing position measures with and without objects in the setup up to 13 mm were possible with a steady green light. A steady green light indicates a situation of no distortion (1).

It will therefore be useful to place the sensors at known positions before each experiment are performed. This will give information about reported mean position measures and variability. When comparing these estimates to the known position, this can reveal whether there are electromagnetic fields that affect the system's position measures or that the sensors just do not function properly at the present test occasion.

4.4 Repositioning

The six test persons showed considerable difference in the ability to reposition the head to a self-elected neutral head position. Studies have shown varying results regarding human ability to reposition the head (5;32). This can be an argument for that there is naturally a variability in neck function between different subjects both for those with and without persistent pain.

In addition, there was no clear tendency of the different test persons to cluster their repositions from the succeeding recordings. It is therefore expected both a variability in performance within subjects and between subjects (17). These findings are an indicator that revealing clinically relevant differences between groups are difficult and demand a very precise measurement instrument, parallel mapping of different qualities and a good classification of the subjects.

The variation in mean position measures were generally larger in y-direction than for x and z. This was seen both for humans with and without movement between repositioning. When the z and x values are so stable, this is an expression of that these six test persons managed to align the head quite well in two out of three directions (±5 mm). The relatively high values in displacement in y-direction (±20 mm) indicate that these test persons moved their head in the direction of retraction/ protraction when instructed to hold the head at rest. This movement is evaluated not being a movement of flexion/ extension because then the displacement also should have been seen in z-direction. This was not the case in this study. Hasan et al (12) tested postural sway in standing and found the same relation between deviations in y- and x-direction as my data suggests.

4.5 Conclusion

The tested instrument is an advanced system for motion tracking that provides stable and repeatable position measurements of a high sampling frequency regardless of the number of sensors connected. The variation in position measurements increases with increased distance to transmitter. For distances closer than 0.5 m the variance is smaller than the system resolution and well within the interest of clinical application. The system is sensitive to metallic objects. When these are introduced close to a sensor, the instrument reports aberrant data. Electromyography electrodes, Teflon and brick can probably be positioned close to sensors without aberrant position data occurring. This instrument should therefore be tested in a rig for control, if other objects or instruments are intended to be used together with it in an experimental setup.

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Appendix 1

Tables A-C specifies the test sequences used for the experiments done not involving human test persons.

Table A: Test sequence used for experiment where sensor is at rest without objects

Part in data file	Description	Comments
1	Start	Sensor in position before recording is started.

Table B: Sensor at rest with introduction of objects

Part in data file	Description	Comments
1	Start of recording	
2	Clean field	Used for analysis
3	Object positioned in field	
4	Object in position (from part 3)	Used for analysis *
5	Object moved and positioned in another position	
…	…	…
N	End of recording	

*the parts of data file where objects are introduced and therefore moved, are not used for analysis. Only those parts that are marked by the stylus marker are used.

This sequence was repeated until all planned objects were positioned in all the relevant positions.

Table C: Repeatability of positions – a sensor moved between two positions

Part in data file	**Description**	**Comments**
1	Start of recording/ Sensor positioned in position a	Screw tighten and human control of if the position is correct
2	Sensor in position a	Used for analysis
3	Sensor made ready for leaving position a	Screw loosed
4	Sensor moved towards position b	
5	Sensor positioned in position b	
6	Sensor in position b	
…	…	…
N	End of recording	

This sequence was repeated until the required repetitions were achieved.

Appendix 2

Tables D and E specifies the test sequences used for the experiments done involving human test persons.

Table D: Test sequence with test persons, experiment one

Part in data file	**Description**	**Instruction by test leader**
1	Start of recording/ «garbage»	Now the test sequence has started. Position your head in NHP* and say «yes» when the position is achieved.
2	NHP	Hold this position for three seconds.
3	Rest	Now you have a break lasting for approximately 30 seconds. // Reposition your head in NHP and say «yes» when the position is achieved.
4	NHP	Hold this position for three seconds.
5	Rest	Now you have a break lasting for approximately 30 seconds. // Reposition your head in NHP and say «yes» when the position is achieved.
6	NHP	Hold this position for three seconds.
7	End of recording/ «garbage»	Test sequence is over.

*neutral head position

Table E: Test sequence with test persons, experiment one

Part in data file	**Description**	**Instruction by test leader**
1	Start of recording/ «garbage»	Now the test sequence has started. Position your head in NHP and say «yes» when the position is achieved.
2	NHP	Hold this position for three seconds.
3	Movement	Move your head towards flexion. Say «yes» when your maximal flexion is achieved.
4	Head in flexion	Hold this position for three seconds.
5	Movement	Move your head towards NHP. Reposition your head in NHP and say «yes» when the position is achieved.
6	NHP	Hold this position for three seconds.
7	Movement	Move your head towards extension. Say «yes» you're your maximal extension is achieved.
8	Head in extension	Hold this position for three seconds.

Part in data file	**Description**	**Instruction by test leader**
9	Movement	Move your head towards NHP. Reposition your head in NHP and say «yes» when the position is achieved.
10	NHP	Hold this position for three seconds.
11	End of recording/ «garbage»	Test sequence is over.