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CLINICAL ASSESSMENT OF GAIT USING LOAD MEASURING FOOTWEAR

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There is a need in orthopaedic surgery for objective measurements to augment the subjective observations of the clinical state of patients who have had weightbearing bone and joint replacements. For this reason, the load measuring footwear programme was initiated. The system enables information to be obtained about the foot-floor load relationship with the patient at rest and in motion. In particular, it was hoped that units of measurement could be used in assessing the patient's clinical progress.

Various techniques such as chrono-photography (Marey 1885), cinephotography (Muybridge 1887), or the use of accelerometers (Liberson 1936), have been used to monitor the gait. Another technique, more suitable for use in clinical practice, is the measurement of the forces acting between the foot and the floor. The forces can be measured by devices set in the floor (Cunningham & Brown 1952), or by devices fitted to the foot (Holden & Muncey 1953, Marsk 1953). Floor mounted force plates can be portable but their position imposes restraints on the walking pattern of the patient. A walk has to be paced to produce the single step measurement, which is in itself a limitation. A more useful number of footsteps can be observed using a pair of longer force plates (Skorecki 1966). Care is necessary to keep the feet on the appropriate plates and difficulties also arise when people use walking aids. These are not portable and constructional factors usually result in these systems being costly.

The alternative method of measuring the forces transmitted through the feet to the floor is to attach the measuring devices to the patient's feet. Provided care is taken with the design of the devices and their

incorporation into footwear, this method is less disruptive to the patient's walking pattern. A system of this type designed without trailing leads would be free of restrictions to particular walk paths and the psychological influence would be reduced. An advantage of the system is that it can be extended to include monitoring of the forces transmitted through walking aids.

Any system for use in a clinic must:

1) impose the minimum restraint on the normal gait activity of the patient,
2) be reliable,
3) be simple to operate,
4) be suitable for commercial production,
5) be relatively cheap and
6) produce records which can be easily interpreted.

Because of these requirements it was decided that the load measuring footwear should measure only the dominant vertical component of the forces acting between the foot and the floor. In addition, the device should respond equally to load over the full area of the foot and not differentiate between different areas of the foot, thus avoiding the complications of multi-trace presentations.

EQUIPMENT AND METHODS

The basic equipment for clinical use consists of instrumented footwear, the receiver unit, a calibration device and some form of recorder. The laboratory and clinical trials were carried out using a prototype receiver and one size of sandal of an open construction which were produced by the Royal Aircraft Establishment, Farnborough. These prototypes were designed around a sandwich transducer and incorporated a transmitter and battery unit in the heel. There were problems in fitting these sandals to differently proportioned feet even within the limited range of length fittings. The lack of balance of the sandal and the flat sole were additional factors which were liable to influence the gait pattern. The design of footwear has been developed as a result of the clinical trials. A modified sports shoe (Figure 1) is used with the transducer replacing the loose insole. The transmitter and battery packs which are housed in pockets on the side of the shoe could alternatively be carried on a belt. The flexible canvas uppers and the lacing down to the toes facilitates the fitting of the shoes to misshapen feet and to feet of differing proportions. The sole of the sports shoe is contoured in two directions giving a rocker feature which is a factor in the design of normal footwear.

A length of wire placed on the floor around the walkway area acts as the "aerial" for the receiver. The main functions of the receiver are to separate the electrical

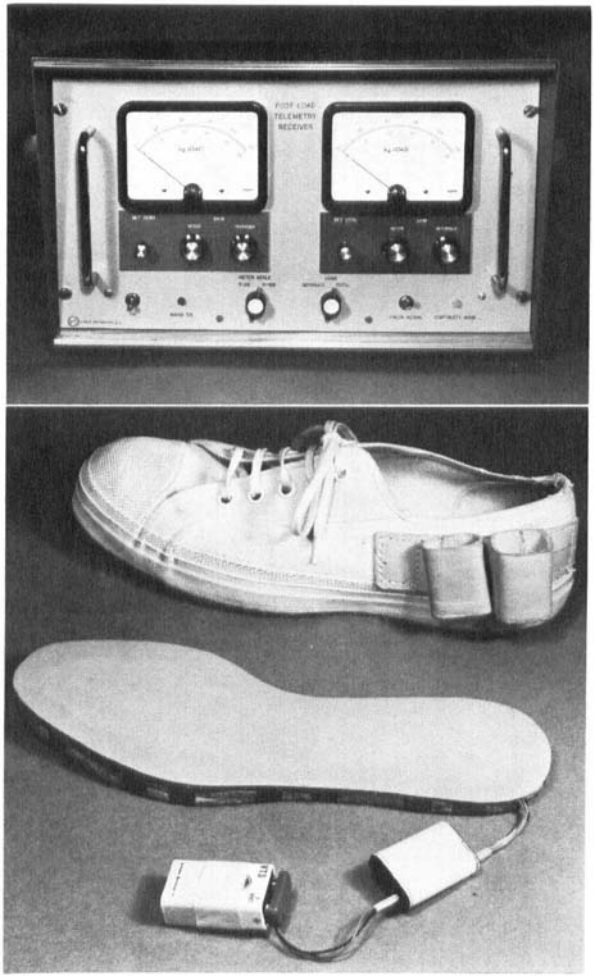

Figure 1. Current design of receiver and footwear.

signals received from the two transmitters and to process these signals to make them suitable for display and recording. The latest design of receiver, shown in Figure 1, incorporates facilities for calibration of the display.

The diagram (Figure 2) sets out the basic details of the recordings. The upper trace is the left foot recording and the lower trace the right foot recording. Load as a percentage of body weight is graphed vertically against time. (Note the horizontal measurement does not represent length of stride.) The swing phase relates to the portion of the cycle when the foot is not touching the ground and no load is transmitted. The stance phase is when the foot is on the ground and a force is transmitted. The two load peaks are sometimes designated "heel and toe". This can be incorrect and more generally applicable terms are depicted on the lower

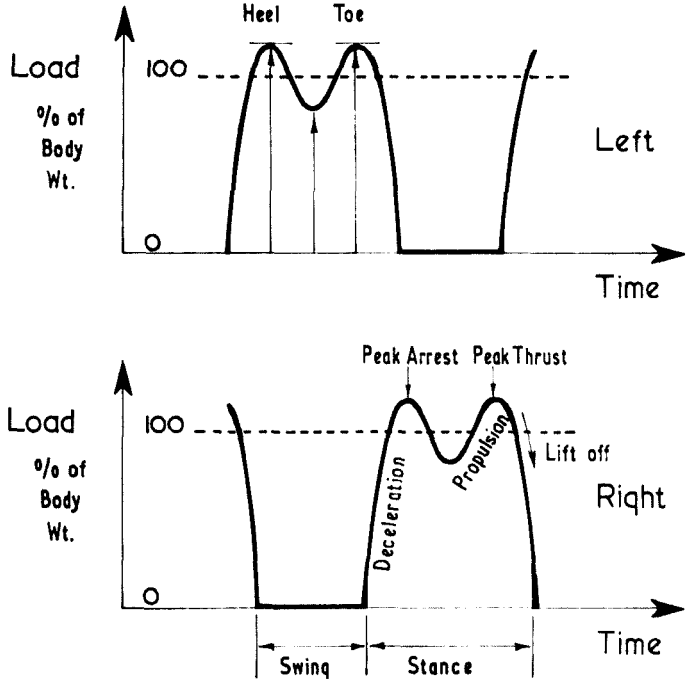

Figure 2. Nomenclature.

trace, namely, "peak-arrest" and "peak-thrust". Additional terms relating to the gait cycle, deceleration, propulsion and lift-off are shown on the relevant sections of the trace.

Normal gait control trials

A series of recordings was made of people with reasonably normal gait characteristics. The criterion of normal gait was that the left and right actions should be similar and that there should be no marked variations in the walk pattern over a period of time. This series proved the consistency of the recordings, the reliability of the system and established the operating procedures.

Comparison with other methods

The patterns obtained from the load-measuring footwear have been compared with published work—for example: from the University of California, Berkeley (1947) and from the Building Research Station, Garston (Harper et al. 1961), with recordings produced by the Charnley and Rydell walkways and directly, using a Kistler force platform. All the recordings show substantially the same characteristics.

Patient recordings

Patient trials were undertaken to obtain information about the following:

1) the acceptability of the system by the patients,
2) the establishment of the operating procedures,
3) the determination of the significant factors of the traces.

The sandals were fitted to the patient, who was then allowed to walk around to become accustomed to the feel of the sandals. The patient was then asked to walk at a comfortable speed. The step rate was timed and this value was used for the setting of an electronic metronome. Recordings were then made with the patient walking with or without sticks or crutches, dependent upon his walking ability. When a recording was made at the time when use of a walking aid had just been discontinued, a recording was made still using the aid to give a continuity of information at the changeover point. When recording after an operation, the same procedures were used to determine the comfortable walking rate. On subsequent occasions, recordings were made at this rate—if there had been no deterioration in the condition of the patient—and at the new increased comfortable rate. Thus, comparisons were made at two rates, one fixed and the other at an increasing rate, a changing value, but comparable through being the fastest comfortable rate at any particular time. On occasions, recordings of the gait were made when the patient thought that the observations had been concluded. There were no significant differences in the quality or quantity of the gait.

Recordings were made of the gait of 16 patients (11 male and 5 female). In eight of these cases (including one bilateral) recordings were taken before and after total hip replacement. A total of 410 recordings of the gait of these patients have been made over a period of 3 years. From these records, some 8000 steps have been studied. A selection of these recordings, from the patients listed in Table 1, has

Table 1.

Case	Sex	Age	Occupation	Condition	Gait feature
1	M	39	Charge Nurse	Osteoclastoma (R) femur	Long-term observation
2	F	64	Housewife	O.A. L and R hips	Use of sticks and crutches
3	M	40	Mechanical Engineer	Radionecrosis (L) head and neck of femur	Stair climbing
4	M	55	Farmer	O.A. (L) hip	First walk after operation
5	M	68	Retired	O.A.	Value of stick

O.A. = Osteoarthritis.

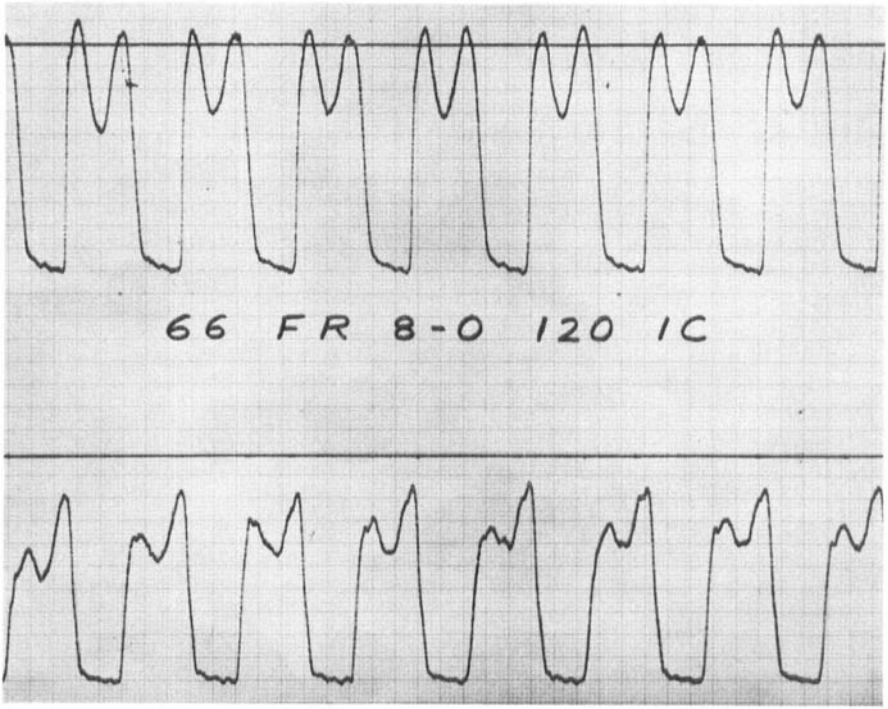

Figure 3. Gait recording 3 (Case 1). 5 weeks after operation; Cadence 80, 2 crutches.

been made to illustrate the changes in gait which related to various clinical features.

FINDINGS

Case 1—Long-term observation

The first gait recording (Figure 3) was made five weeks after the replacement of an upper third right femoral prosthesis in which the intramedullary stem had fractured. The maximum comfortable cadence, using two crutches, was approximately 80 steps per minute. Only 50 per cent load was taken on the right foot and showed that the patient was controlling the deceleration phase and protecting the heel strike. Three weeks later the patient was at the stage where he could walk at 120 steps per minute using one crutch held in the left hand (Figure 4). The load on the left foot had increased and the peaks were more rounded. The load taken on the right foot had also increased. Subsequent to the controlled action of the deceleration phase it showed

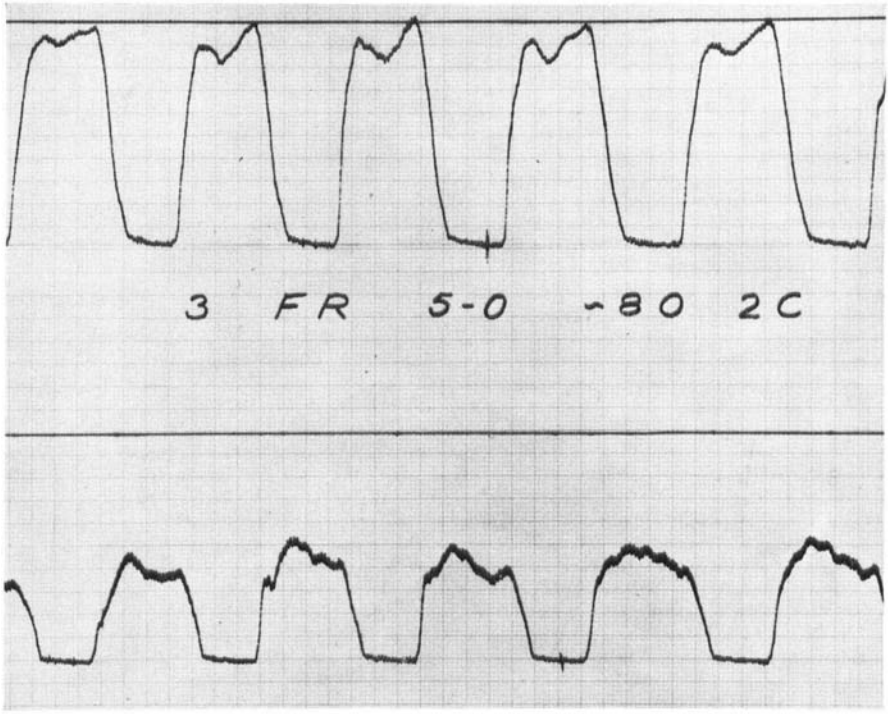

Figure 4. Gait recording 66 (Case 1). 8 weeks after operation; Cadence 120, 1 crutch.

the greater ability of the limb to sustain or generate an increased thrust-off load. The overall pattern of loading was now more normal. Further recordings were made 14 weeks after operation, when the patient was able to walk unaided at a cadence of 120 (Figure 5). The overall pattern was smoother and showed a slight increase of heel and toe loads on the right foot. The left foot pattern had a deeper trough which was a result of a more vigorous uninhibited gait action. The patient's "new standard" gait at 120 unaided, 45 weeks after operation, is illustrated in Figure 6. The pattern of the right foot loading had improved still further in that there was increased amplitude of the first peak, illustrating a less restrained action at heel strike.

Conclusions

This series of recordings has shown the progression of the patient over the period of time up to the attainment of his new "normal" gait.

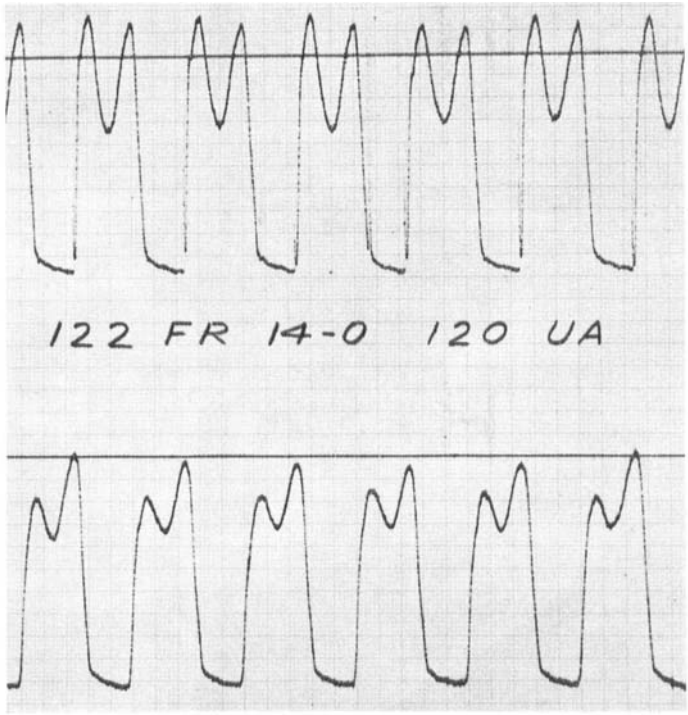

Figure 5. Gait recording 122 (Case 1). 14 weeks after operation; Cadence 120, unaided.

Case 2—Use of sticks and crutches

Two weeks and 4 days after operation for a right total hip replacement (Ring), using two crutches at a low cadence, the waveforms were irregular, with only 40 per cent of the body weight being taken on the right foot (Figure 7).

Only 2 days later a marked improvement in the pattern of the gait was observed (Figure 8). The pattern was smoother, the peaks had appeared and the cadence had increased to 80. This improvement was coincident with a change from using crutches to using two sticks. With one stick (Figure 9) there was an increase in the peak amplitude of the left foot loading, compared with the values recorded in Figure 8. Comparing Figure 9 (1 stick) with Figure 8 (2 sticks), the patterns of the left and right gait were not as smooth and there was an increased irregular load observed on the left with a sharp thrust peak on the right. This is similar to a pre-operative observation that the patient was not

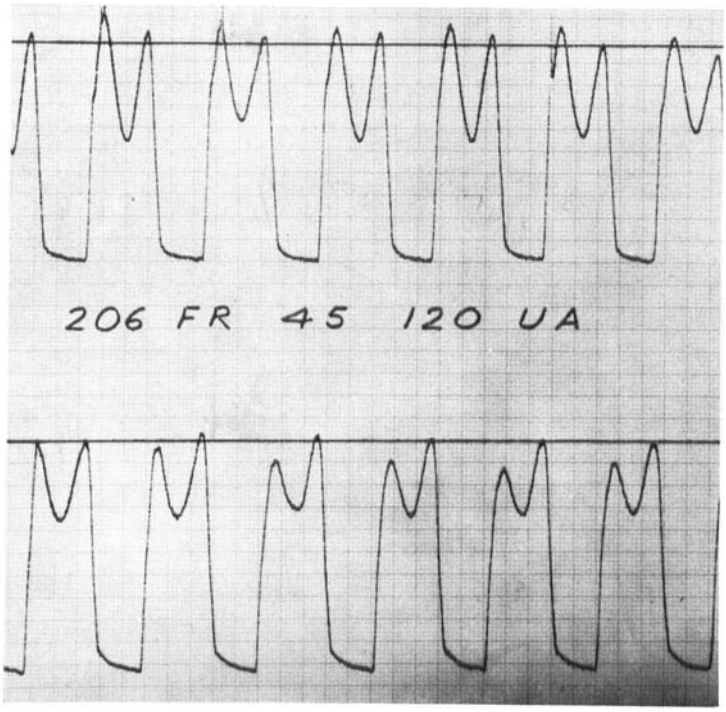

Figure 6. Gait recording 206 (Case 1). 45 weeks after operation; Cadence 120, unaided.

as proficient in the use of one stick. Figures 8 and 9 indicate that the patient required the use of two sticks.

Two additional recordings were taken 3 weeks after operation of walking at the slow cadence measured after operation—45 per minute—and using two sticks in two ways, in phase (Figure 10) and alternating (Figure 11). When the sticks were used in phase there was an irregular loading. However, when the patient walked using the sticks in the alternating mode the loading pattern was much smoother. These recordings illustrated the patient's difficulty in walking with sticks in phase—the recommended method. The patient preferred to use the sticks in the alternating mode.

Conclusion

The recording enabled:

1) an assessment to be made of the value using two sticks compared with one stick,

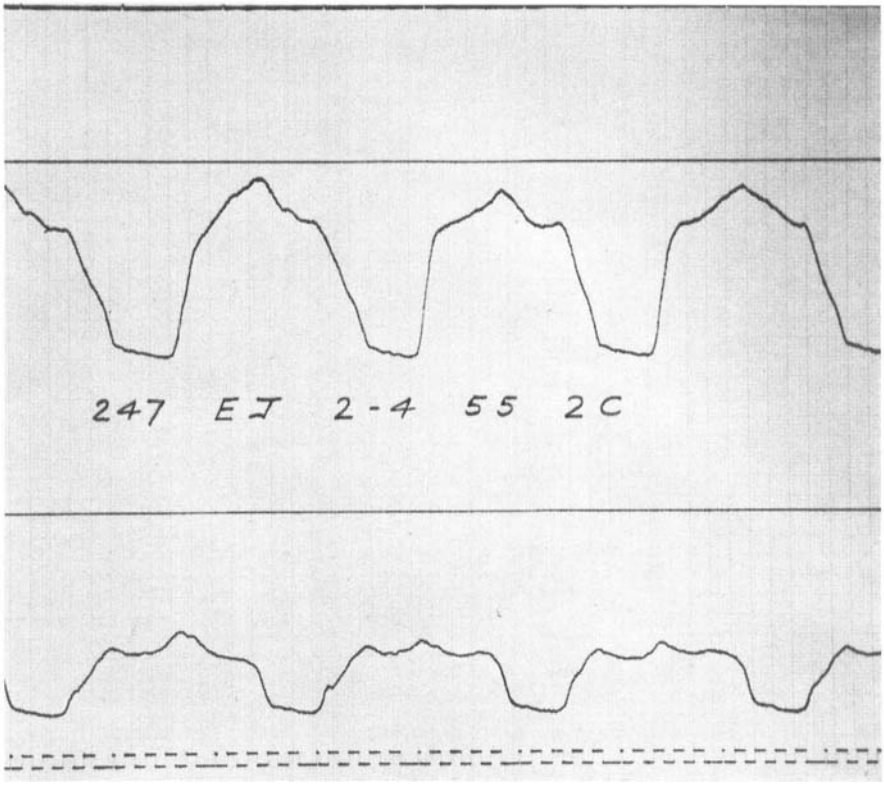

Figure 7. Gait recording 247 (Case 2). 2 weeks and 4 days after operation; Cadence 55, 2 crutches.

2) an assessment to be made of the value of crutches compared with sticks,
3) an assessment to be made of the value of the mode of use of walking aids.

Case 3—Stair climbling

Figure 12 shows a gait recording of the patient, 2 years after operation for replacement of the upper femur, climbing up and down stairs, without a walking aid, but using a handrail. In ascending the stairs there was a slower rate of rise of load in the deceleration phases of both the left and right foot loads since the person was raising the body weight. In descending the stairs, there was a rapid development of the

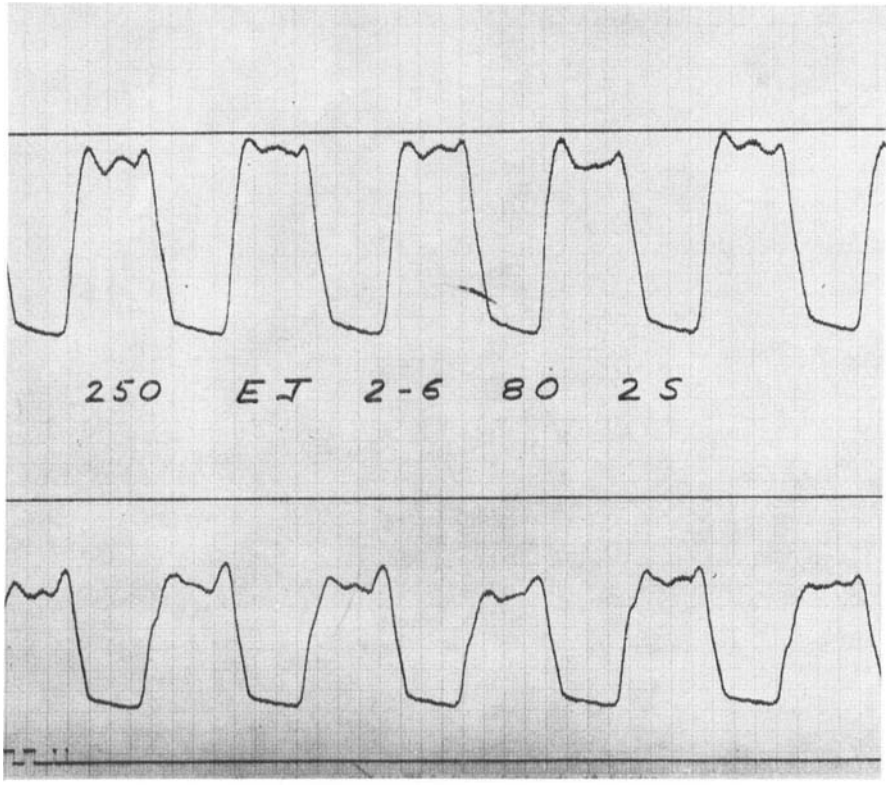

Figure 8. Gait recording 250 (Case 2). 2 weeks and 6 days after operation; Cadence 80, 2 sticks.

load sustained by the feet i.e. a higher rate of deceleration. There was about 80 per cent of the body-weight load transmitted through the left foot on descent and 85 per cent on ascent. On the right foot a double peak curve was produced by a gait which was ball of foot only, not heel and toe, on both ascent and descent.

Conclusion

1) The waveform developed during walking does not indicate the sequential pattern of application of load to the foot, normally heel and toe.
2) In climbing stairs the peak-thrust exceeds the peak-arrest, while in descent the peak-arrest is greater.

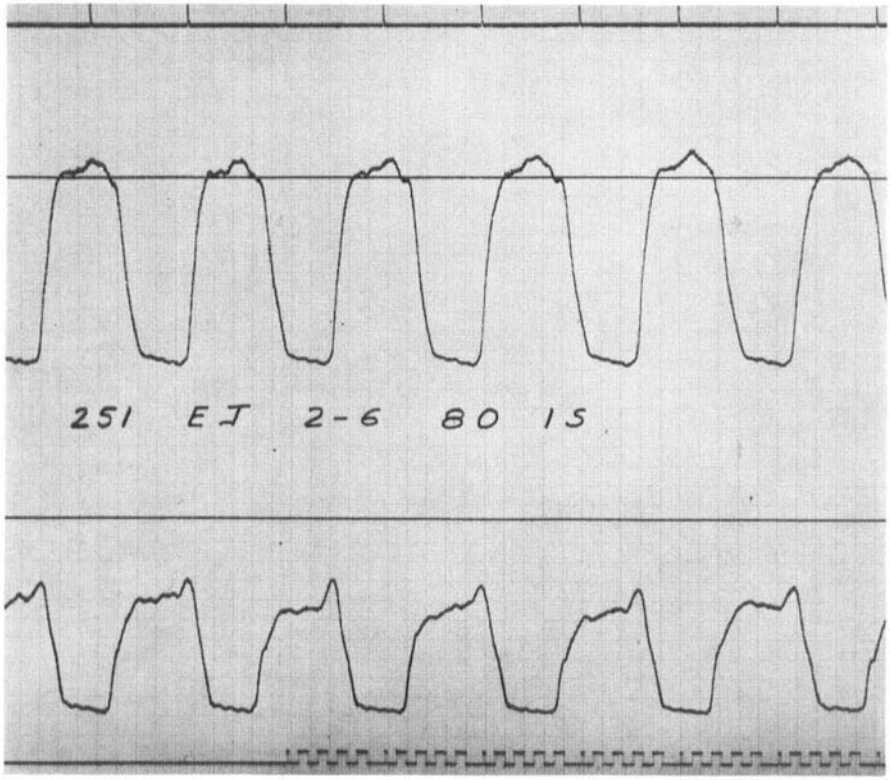

Figure 9. Gait recording 251 (Case 2). 2 weeks and 6 days after operation; Cadence 80, 1 stick.

Case 4—First walk after operation

One recording (Figure 13) of this patient has been selected as it shows the very first attempt to walk, using two crutches almost 3 weeks after operation for a custom-made femoral replacement. The cadence was extremely low as one step took about 8 seconds. Load was taken on the unaffected leg for 95 per cent of the step cycle. Although the left foot was in contact with the ground for almost the same length of time, only a very small proportion of body weight was allowed onto the foot.

Conclusion

Recordings taken in the critical early stages after operation can assist the patient in mastering crutch techniques and avoid high loads being

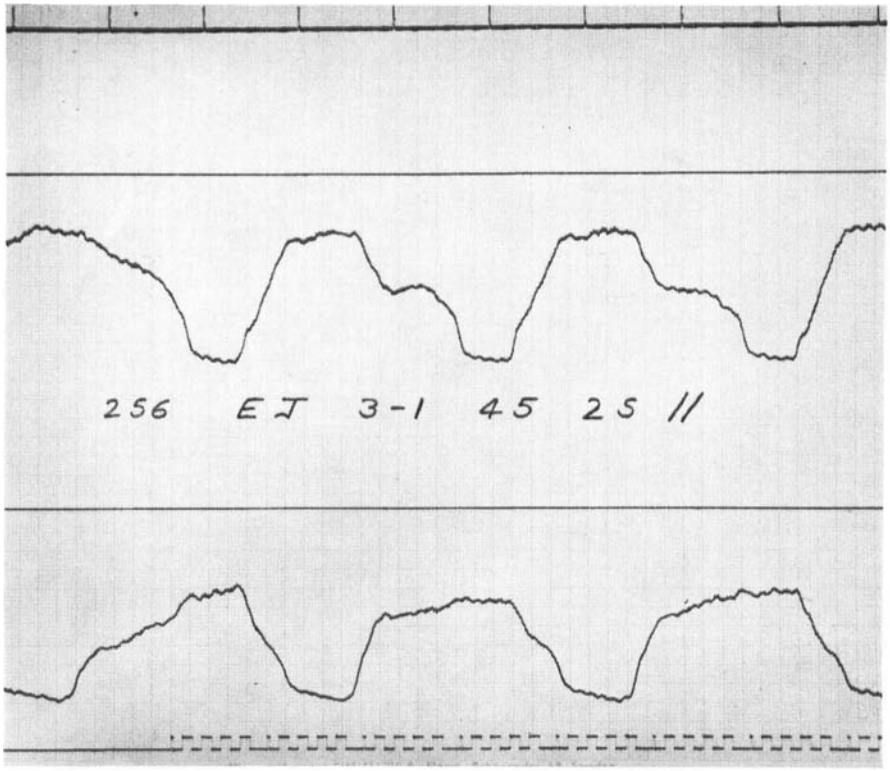

Figure 10. Gait recording 256 (Case 2). 3 weeks and 1 day after operation; Cadence 45, 2 sticks in phase.

taken on the leg. The recordings give information about the value of loading which neither the clinician nor the patient can otherwise estimate.

Case 5—Value of stick

This case has been selected to demonstrate how useful information can be obtained quickly and simply from the gait recordings. The recordings were made 64 weeks after an all cobalt-chromium-molybdenum alloy Stanmore total replacement of the left hip of a male patient, aged 68 years. He was virtually pain-free and although advised to use a stick, obviously walked without one. He stated that he used the stick mostly to maintain balance and put little weight on it (estimated at 5 kg).

His gait was recorded both unaided and with a stick in his right

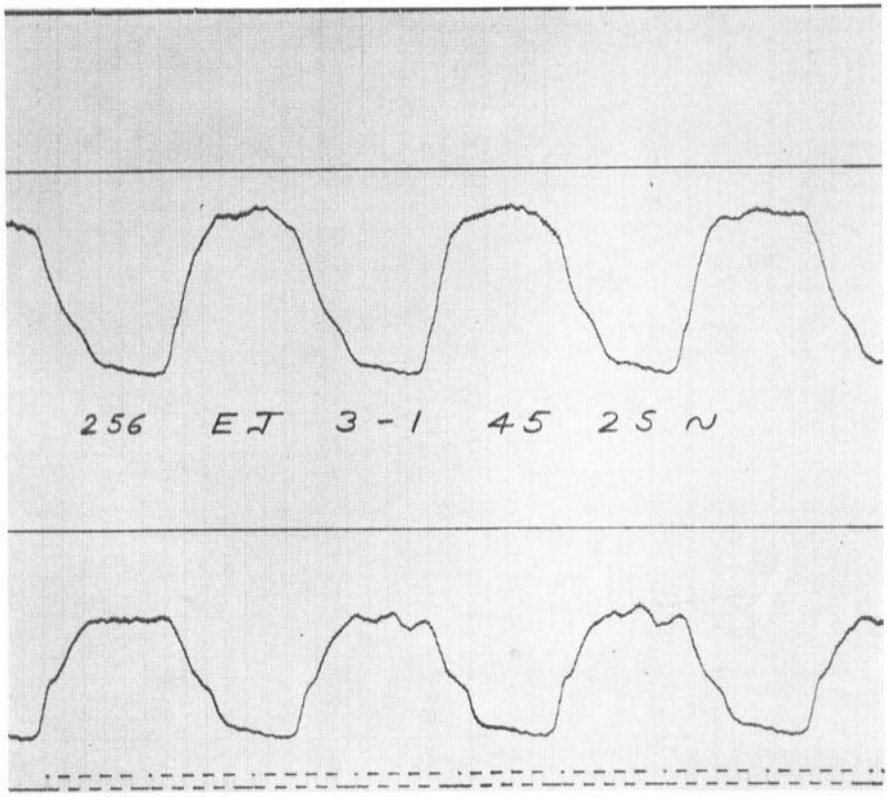

Figure 11. Gait recording 256 (Case 2). 3 weeks and 1 day after operation; Cadence 45, 2 sticks alternating.

hand. These recordings are shown in Figure 14. The traces with a stick show the following factors, compared to walking unaided:

1) There is a slight reduction in left load peaks.
2) There is a slight increase in right load peaks.
3) The left double peak toe load is eliminated.
4) There is a deeper right inter-peak trough.
5) The right heel and toe peaks are smoother, more rounded.

Conclusion

This case illustrates clearly the value of the monitoring system.

1) The advantage of continuing with the stick after 64 weeks is shown. Both left and right loadings are more even compared with the gait when no stick is used.

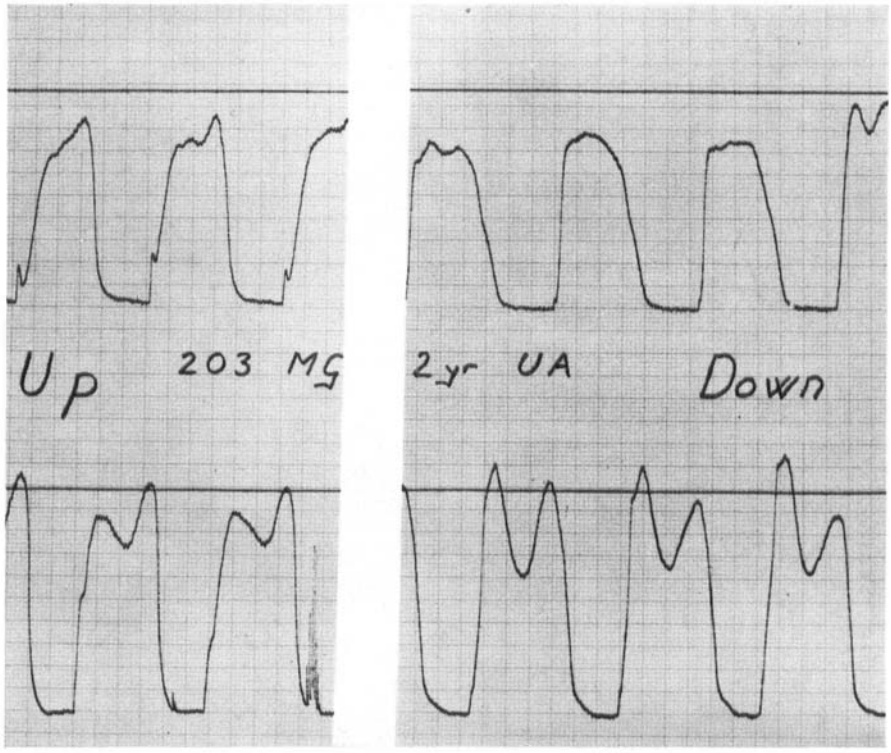

Figure 12. Gait recording 203 (Case 3). 2 years after operation; Up and down stairs unaided.

2) Evidence was provided that the surgeon judged correctly that a walking aid was required.
3) The display of the trace to the patient should convince him of the necessity of following the surgeon's advice.

Progress chart

The vertical component of the load transmitted through each foot can be measured and used to assess the clinical progress of a patient following treatment. Average values of the maximum load obtained from measurements of the recordings of the gait of Case 1 over a period of 40 weeks are shown in Figure 15. The relative loading is shown and how it changes with different walking aids.

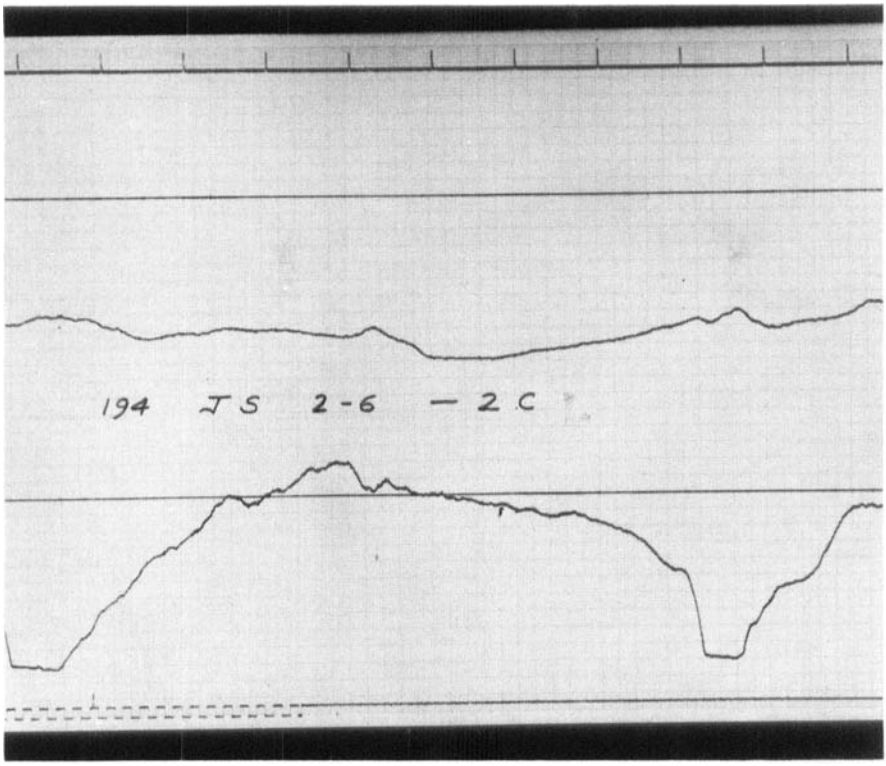

Figure 13. Gait recording 194 (Case 4). 2 weeks and 6 days after operation; 2 crutches.

GENERAL CONCLUSIONS

The recordings give the following information:

1) the magnitude of the vertical component of the loads transmitted through the feet,
2) the characteristic gait or pattern of the loading,
3) the duration of the phases of the loading cycle,
4) the rate or cadence of walking,
5) the velocity of the patient.

Observation and measurement of the above features of the recordings give the following clinical information about the patient:

1) the proportion of body weight transmitted by the feet walking unaided and when using aids, and the changes in these loadings with time.

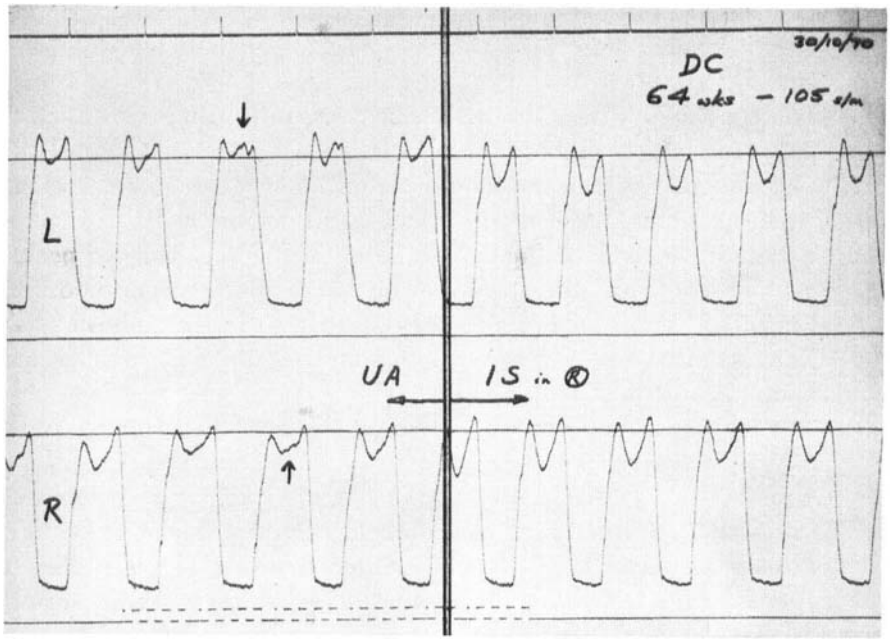

Figure 14. Gait recording 356/357 (Case 5). 64 weeks after operation; Cadence 105, unaided/1 stick.

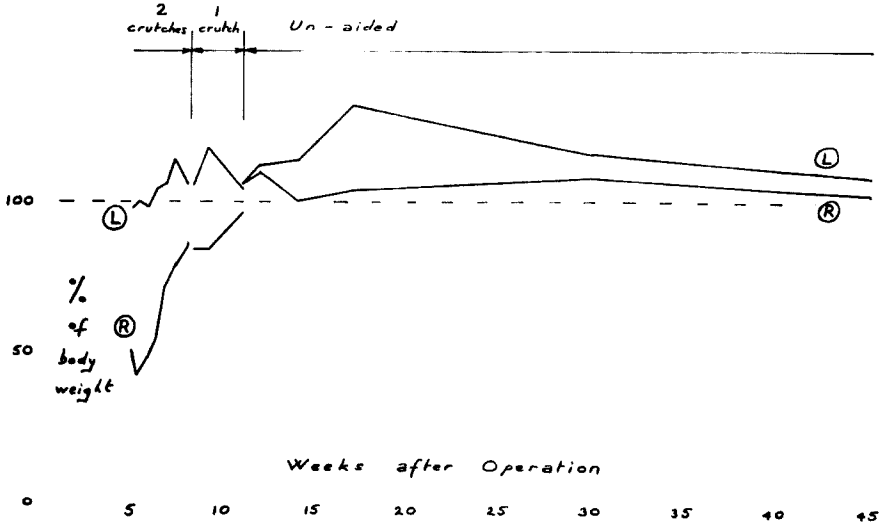

Figure 15. Progress chart (Case 1).

2) The relative value of heel and toe peak loadings.
3) The absence, followed by the reappearance of heel and toe peak loadings and the order of this reappearance.
4) The time over which the heel load rises, indicating the effect of the patient controlling the heel strike.
5) The time over which the toe-off action takes place, indicating the effect of the patient controlling this phase of the walk.
6) The characteristic of the trough between the heel and toe peaks. This loading can indicate the influence of the freedom or otherwise of the other leg in its swing—non-weightbearing phase.
7) The influence on the pattern of loading with alternative types and methods of use of walking aids.
8) The influence of treatment on the rate or cadence of walking, directly relatable to the cadence.

The recordings have confirmed, contradicted and added to clinical observations. In general, the sandal method has proved acceptable to the patients, who have been able to walk in an apparently normal manner. The narrow corridor has provided a reassurance, both for physical support and lack of "public" observation and the length of the corridor has proved adequate in providing a sufficient number of steps.

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